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Fire Propagation in Concurrent Flows

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January 1989

Prepared for
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
Center for Fire Research
Gaithersburg, MD 20899

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NIST Grant No. 60NANB7D0737

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FIRE PROPAGATION IN CONCURRENT FLOWS

NBS Grant No. 60NANB7D0737

Final Progress Report

August 1, 1987 - July 31, 1988

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August 1988

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ABSTRACT

The research tasks completed during this reporting period include an experimental study of the effect on the spread of flames of the turbulence intensity of an opposed air flow, and a theoretical analysis of the concurrent spread of flames over thin fuels. Both studies are in our opinion important contributions in the study of the fame spread process. The results of the experimental study show that the flame spread process is significantly affected by the flow turbulence intensity for flames spreading over both thin and thick fuels. For a fixed flow velocity, the spread rate decreases as the turbulent intensity is increased. This appears to be due to the turbulent convective cooling of the fuel surface and gas in the vicinity of the flame front. Also observed is that extinction of the flames occurs at lower velocities as the turbulent intensity increases. The results of the theoretical analysis, which are in good agreement with previous experimental measurements, give detailed information about the flame structure and mechanisms of flame spread. It is shown that the flame length and consequently the rate of flame spread, are strongly dependent on the interaction between the pyrolysis and burn-out fronts.

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1. INTRODUCTION

The research performed during this reporting period forms part of an on-going research program aimed at the study of the mechanisms controlling the spread of fire in the presence of a forced flow of air, or other oxidizing gas. The oxidizing flow interacts with the fire and therefore affects its rate of spread. The final objective of the research program is to provide information about the spread of fire that can be used in the development of models of fire growth in rooms and of test methods of the flammability of materials.

The tasks conducted during this period include experimental observations of the effect on the opposed flow flame spread of the flow turbulence intensity, and numerical modeling of the concurrent spread of flames over thin fuels. We feel that both works are important contributions in the study of the flame spread process.

In most practical cases the spread of fire occurs under turbulent flow conditions. Flow turbulence can affect both the heat transfer and the chemical kinetic mechanisms that control the flame spread process, both by convective cooling and gas mixing. The determination of the role of these mechanisms is necessary to understand and predict the spread of fire under realistic conditions. With the exception of the works of Orloff, et al. (15th Int. Symp. Comb. p. 183, 1975) and Saito and co-workers (1st Int. Symp. Fire Safety, p. 75, 1986; 24th Nat. Heat Trans. Conf. 1987) for the upward turbulent spread of flames, no systematic experiments have been performed to date to determine the effect of turbulence on the flame spread process. This is the objective of this work. The work consists of a parametric study where the velocity and turbulence intensity of an air flow are varied to study their effect on the rate of flame spread over thick and thin fuels.

With regard to the theoretical task reported here, very few analyses have been published to date of the concurrent spread of flames over a thin combustible. The works of Markstein and de Ris (14th Int. Symp. Comb. p. 1085, 1973) and Fernandez-Pello (Comb. Flame, 31, p. 135, 1978; Comb. Flame, 36, p. 63, 1979) provide only approximate analytical solutions of the problem, which can only describe partially the experimental observations. The present work provides a more accurate description of the process by removing some of the critical assumptions made in previous analyses. The results describe and agree well with the experimental observations.

In the following section a summary is provided of the above studies. Papers prepared for publication describing these studies are included in this report in the form of appendices.

II. RESEARCH PROGRESS

II.1 Experiments of Flame Spread in an Opposed Turbulent Flow

An experimental study has been conducted of the influence on the spread of flames over the surface of thick and thin solid combustibles of the turbulence intensity of an air flow opposing the direction of flame propagation. The experiments are conducted in a facility specifically designed to perform flame spread experiments consisting of a small scale combustion tunnel and supporting instrumentation based primarily on optical and thermocouple measuring methods. The turbulence intensity in the tunnel test section is varied by means of grids and perforated plates of different sizes placed at the exit of the tunnel converging nozzle. The velocity and turbulence intensity of the flow field are measured with a one component Laser Doppler Velocimeter. The flame spread rate is obtained visually timing the pass of the flame front through marks placed at fixed distances along the combustible surface.

II.1.1 Thick PMMA Sheets

The measurements of the flame spread rate over PMMA sheets as a function of the opposed air flow velocity are shown in Fig. 1 for several values of the turbulence intensity. It is seen that the spread rate first increases sharply as the flow velocity is increased and then decreases. The initial increase appears to be the result of a transition from a mixed flow type flame spread to a forced flow one. At low flow velocities, normal buoyancy tends to lift the flame from the fuel surface, which results in reduced heat transfer from flame to fuel and consequently in a slower spread rate. The decrease of the flame spread rate with the opposed flow velocity at higher air velocities is the result of gas phase chemical kinetics effects. As the opposed flow velocity increases the residence time of the fuel vapor/air mixture ahead of the flame decreases. For constant chemical time this results in a slowdown of the combustion reaction at the flame leading edge that sustain the propagation of the flame. This effect is observed to occur at all turbulence intensity levels.

The effect of turbulence intensity on the flame spread rate can also be deduced from the results of Fig. 1. This is presented in Fig. 2 for three value of the flow velocity. It is seen that for all flow velocities the flame spread rate first increases and then decreases as the turbulent intensity increases. The maximum occurs at approximately 6% of the turbulent intensity. This result may reflect the differences in the boundary layer that take place during the transition from laminar to turbulent flow. For PMMA, heat conduction through the solid is an important flame spread mechanism. Thus, the thinning of the boundary layer that occurs as the flow changes from laminar to turbulent should result in an increase of the flame spread rate because the heat transfer to the

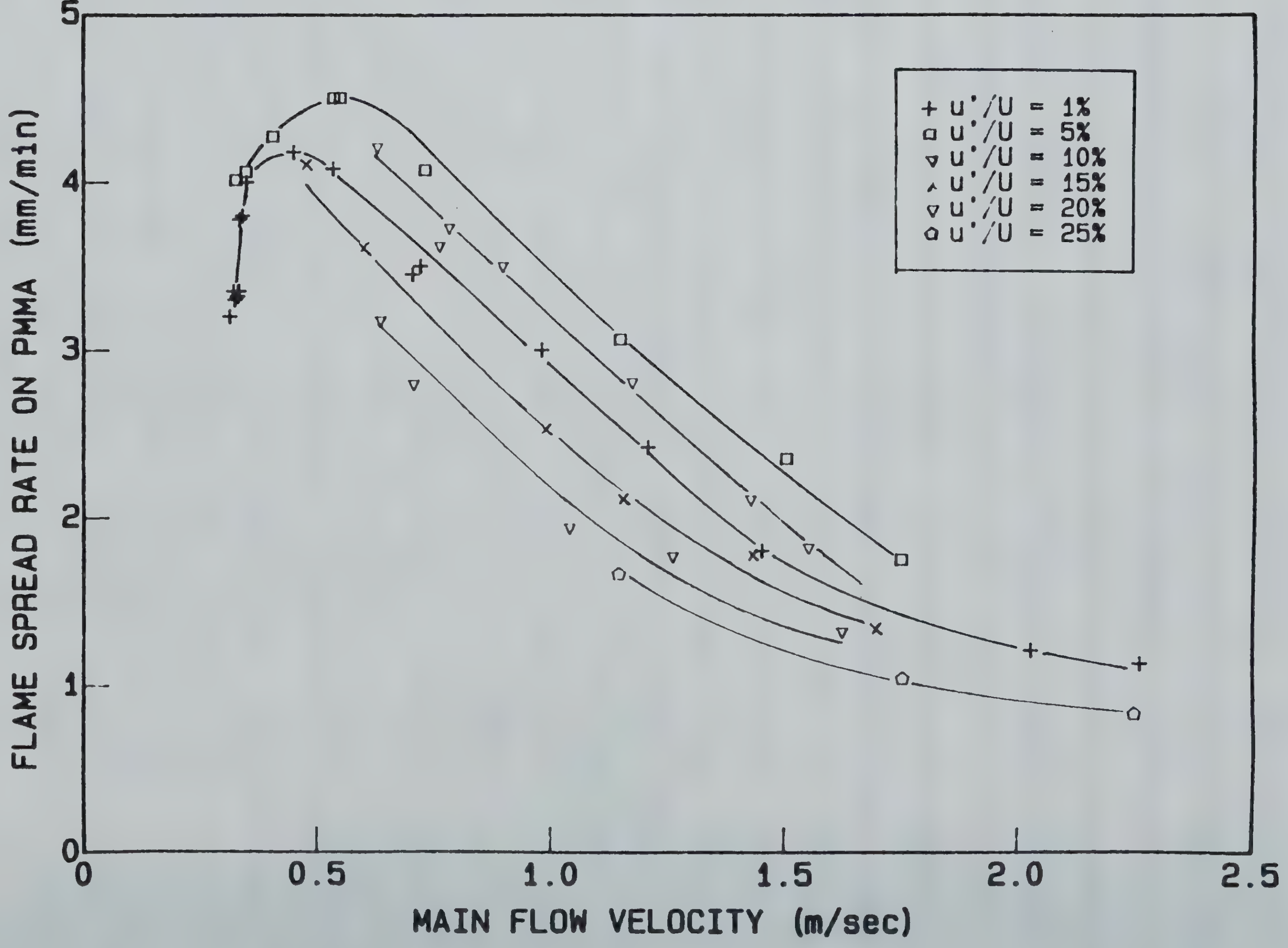
+ u'/U = 1%
□ u'/U = 5%
▽ u'/U = 10%
x u'/U = 15%
▽ u'/U = 20%
⬠ u'/U = 25%
FLAME SPREAD RATE ON PMMA (mm/min)
0
1
2
3
4
5
MAIN FLOW VELOCITY (m/sec)
0
0.5
1.0
1.5
2.0
2.5

FIGURE 1.

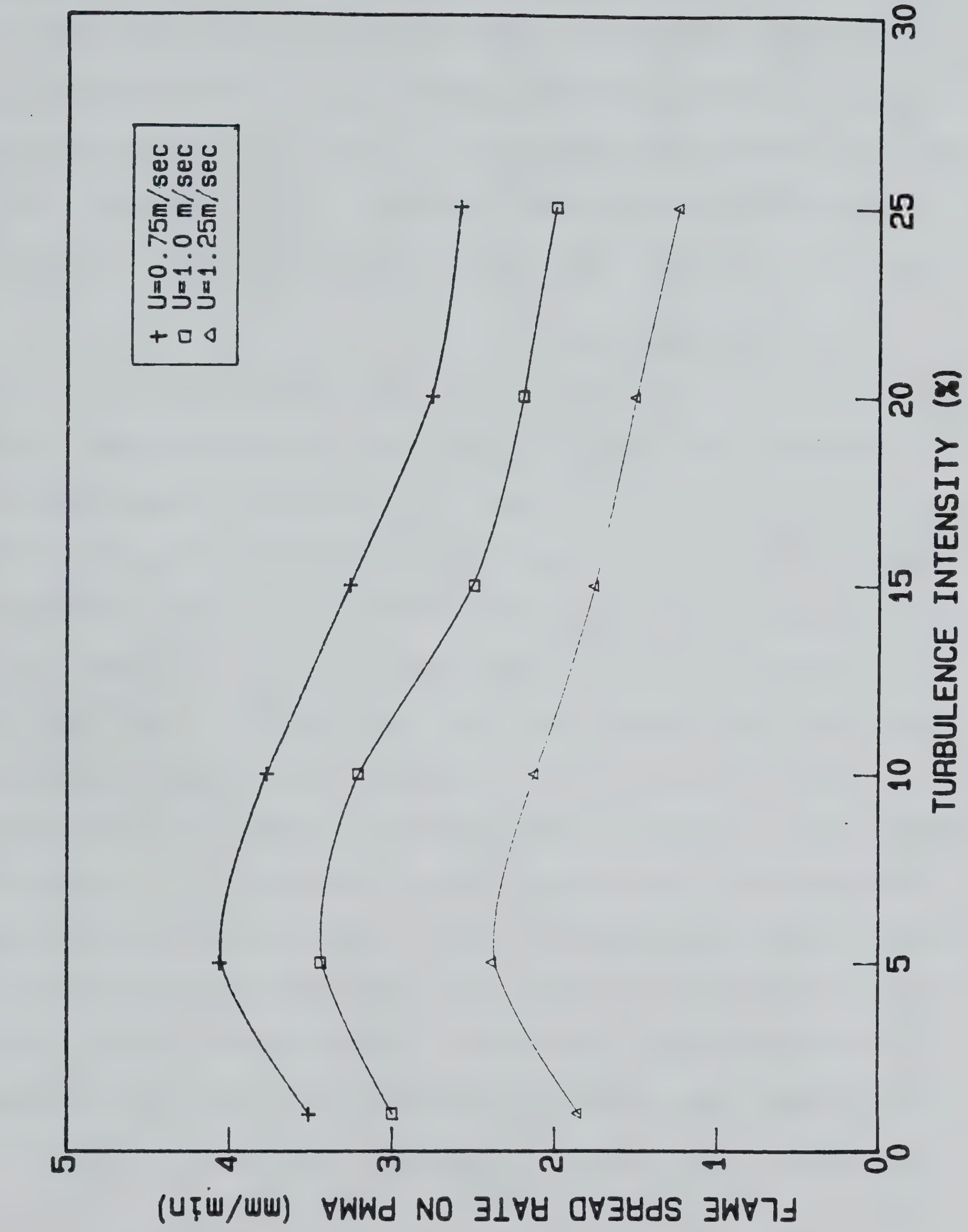
FLAME SPREAD RATE ON PMMA (mm/min)
TURBULENCE INTENSITY (%)
0
1
2
3
4
5
0
5
10
15
20
25
30
+ U=0.75m/sec
□ U=1.0 m/sec
△ U=1.25m/sec

FIGURE 2.

solid increases. At low turbulence intensities this effect appears to be more important than the potential enhancement of the fuel convective cooling that should occur as the flow becomes more turbulent. Another possible mechanism that should be considered is an enhancement by the flow turbulence of the fuel vapor and air mixing at the flame leading edge, which could result in a stronger gas phase reaction and consequently in a faster flame spreading velocity. Although we think that the former mechanism is the more likely to occur, there is not enough available information at this point to resolve the issue.

II.1.2 Thin Paper Sheets

The results of the measurements of the variation with the air flow velocity and turbulence intensity of the flame spread rate over thin paper sheets are presented in Fig. 3. In this case, the flames do not propagate (extinguish) in gas flows with velocities larger than 1.5 m/s. The low flow velocities at which the tests had to be conducted limited the maximum range of turbulence intensities attainable to 15%. From the results of Fig. 3 it is seen that for all turbulence intensities the spread rate decreases as the opposed gas velocity increases. The decrease in the low velocity region, however, is small. This again appears to be the influence of buoyancy on the flame spread process at low flow velocities. This influence is not as noticeable as in the case of PMMA probably because with paper the flames are smaller and consequently less buoyant. The stronger decrease of the flame spread rate with the flow velocity observed for the larger air velocities appear to be the combined effect of convective cooling and weakening of the chemical reaction (smaller residence time) that take place as the opposed flow velocity increases.

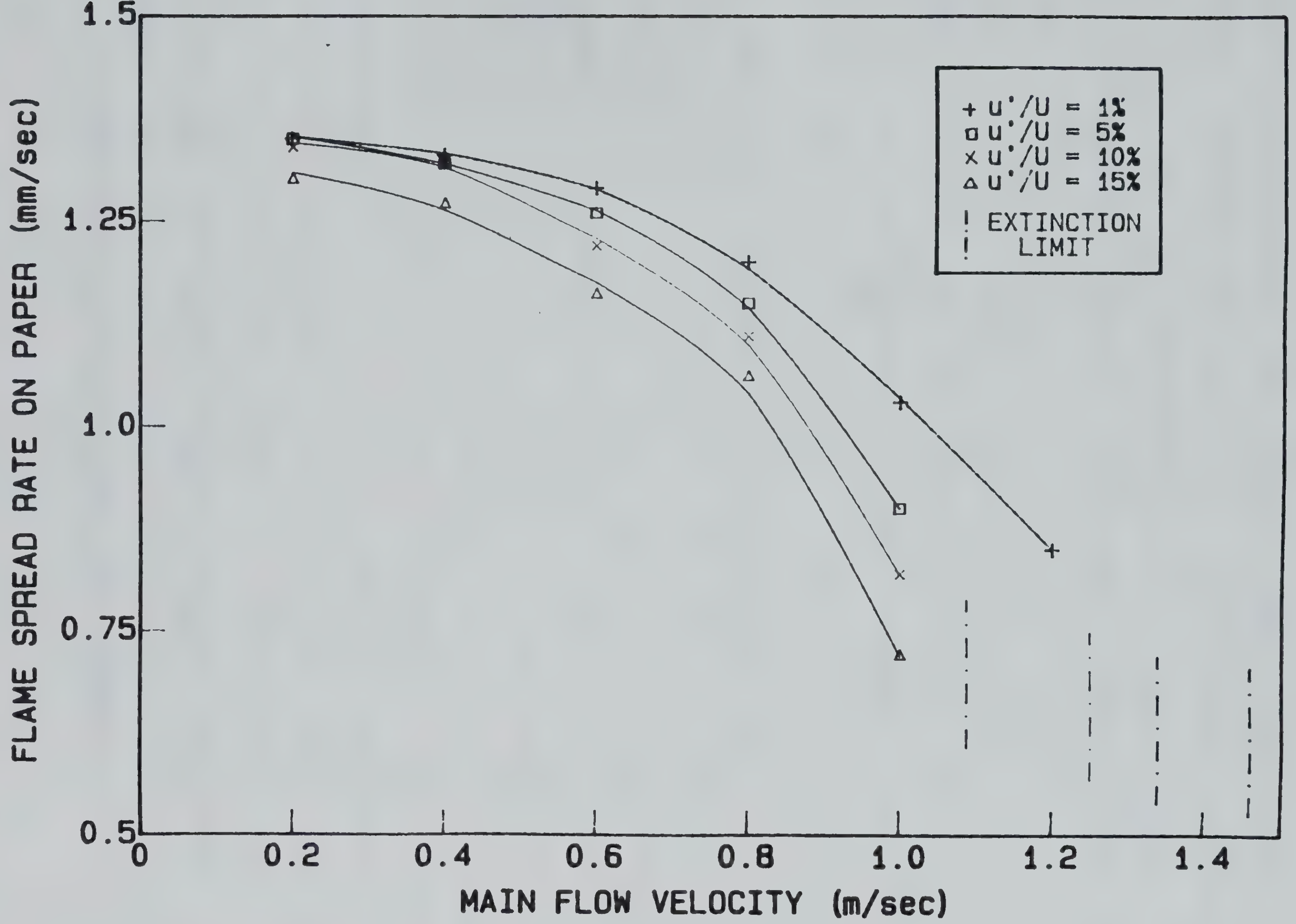
FLAME SPREAD RATE ON PAPER (mm/sec)
1.5
1.25
1.0
0.75
0.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
MAIN FLOW VELOCITY (m/sec)
+ u'/U = 1%
□ u'/U = 5%
× u'/U = 10%
△ u'/U = 15%
EXTINCTION LIMIT

FIGURE 3.

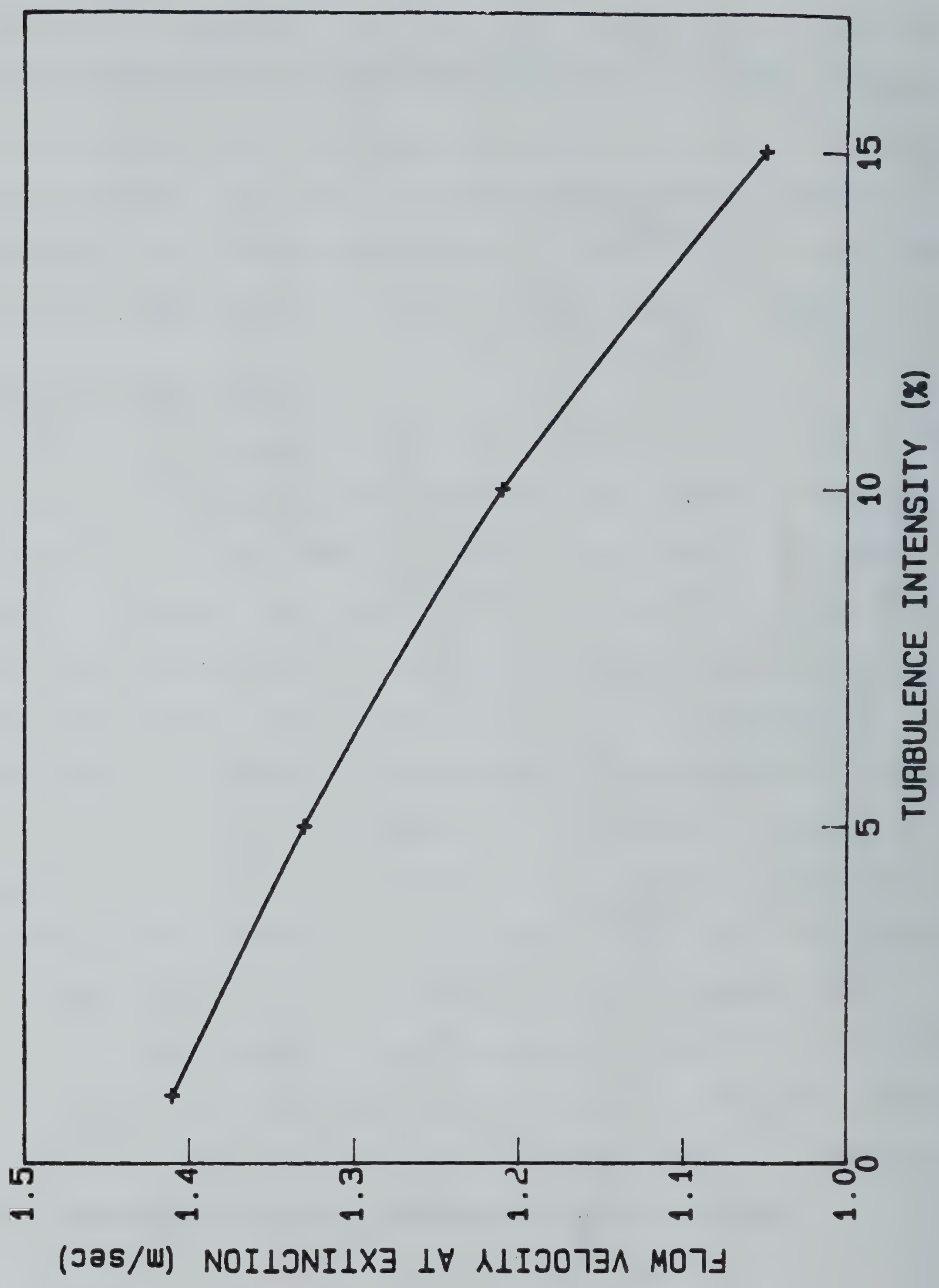
FLOW VELOCITY AT EXTINCTION (m/sec)
1.0
1.1
1.2
1.3
1.4
1.5
TURBULENCE INTENSITY (%)
0
5
10
15

FIGURE 4

An interesting result obtained in these experiments is the effect of flow turbulence intensity on the extinction of the flame. This is shown in Fig. 4 where the gas velocity at which extinction is observed is presented as a function of the turbulence intensity. It is seen that flame extinction occurs at lower flow velocities when the turbulence intensity is increased. This result, although it is in general agreement with the other flame spread results, is somewhat unexpected since turbulence is often viewed as a means to enhance fuel combustion processes.

A paper reporting this result will be presented at the 1988 Fall Meeting/Western States Section of the Combustion Institute. It will also be submitted for publication in Combustion and Flame. The paper is included in this report as Appendix A.

II.2 Model of Concurrent Flame Spread Over a Thin Charring Solid

A theoretical model has been developed of the spread of a flame over the surface of a thin combustible solid in a gas flow moving in the direction of flame propagation. The combustion reaction and the solid pyrolysis are modeled respectively with a one-step, second order, and with a zero order Arrhenius reaction. The charring of the solid is modeled by treating the solid as a two component material, the combustible component that gasifies, and the char that remains occupying the initial solid volume. To simplify the mathematical solution of the problem, a Hagen-Poiseuille flow is prescribed, thus eliminating the need for using the momentum conservation equations. The transient, reactive, gas phase balance equations of energy and species coupled at the interface to the solid phase energy equation are solved numerically to describe the evolution of the flame and soot properties, and through them to predict the variation with time of the flame, pyrolysis and burnout distances and their dependence on the flow velocity.

The model is applied to the description of the spread of flames over paper sheets in a concurrent air flow. In Fig. 5 the predicted variation with time of the flame, pyrolysis and burnout distances are presented for several flow velocities. The experimental data of Loh and Fernandez-Pello (1stl Int. Symp. Fire Saf. Sci., 65, 1986) are included for comparison. In Fig. 6 the predicted dependence on the flow velocity of the steady state pyrolysis spread rate is also presented with the comparison with the experiments. It is seen that the predictions of the model agree well with the experiments. Particularly important is the description of the transition of the flame spread process from an initial accelerative stage to a final steady state. The transition is determined by the interaction between the progress of the pyrolysis and the burn-out fronts, and their effects in the flame length. According to boundary layer analyses, the model predicts a spread rate that increases, although weakly, with the flow velocity, while the experiments show a spread rate that first increases at low flow velocities and then becomes constant as the flow velocity is increased. Some reasons for this potential disagreement are discussed in the work. Finally the predicted flame extinction limit due to increased concurrent velocity is very close to the experimentally determined value.

This work was performed in collaboration with Dr. Di Blasi of Naples University, Italy. A paper reporting the results has been accepted for publication at the Proceedings of the 22nd Symposium International on Combustion, held in Seattle, Washington, August 1988. It is included in this report as Appendix B.

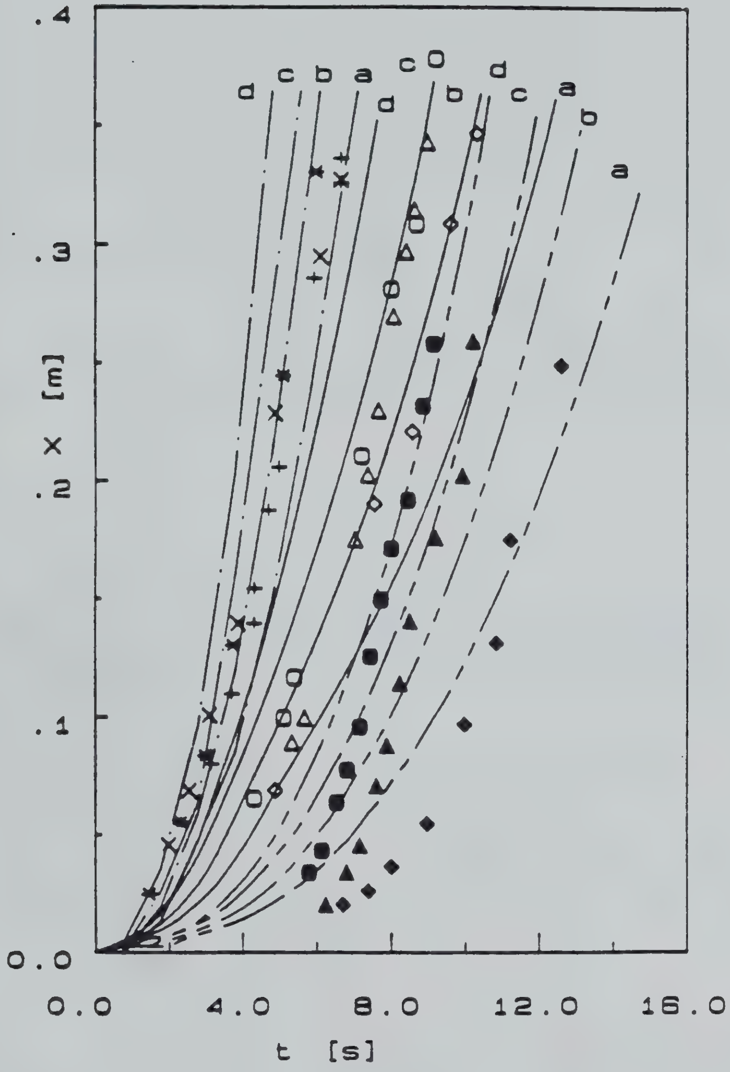

FIGURE 5.

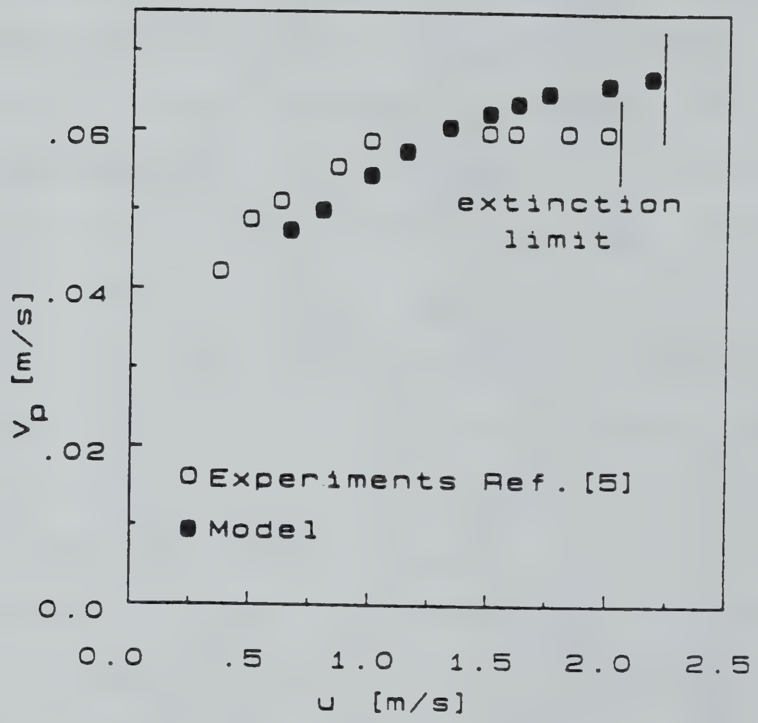
.06
.04
.02
0.0
V_p [m/s]
0.0
.5
1.0
1.5
2.0
2.5
u [m/s]
extinction limit
○ Experiments Ref. [5]
● Model

FIGURE 6.

II.3 Publications and Presentations

Kodama, H., Miyasaka, K. and Fernandez-Pello, A.C., "Extinction and Stabilization of a Diffusion Flame on a Flat Combustible Surface with Emphasis on Thermal Controlling Mechanisms," Combustion Science and Technology, 94, 1-6, pp. 37-50 (1987).

Amos, B., Kodama, H. and Fernandez-Pello, A.C., "An Analysis of the Ignition by Vapor Radiation Absorption of Vaporizing Fuel at Zero Gravity," presented at the AIAA 25th Aero. Sci. Meeting, Reno, Nevada, 1987. Also Progress in Aeronautics and Astronautics (in press), 1988.

Amos, B., "Ignition and Flame Propagation Studies Over a Flat Fuel Surface," Ph.D. Thesis, Department of Mechanical Engineering, University of California, Berkeley, August 1987.

Di Blasi, C., Cresticelli, S., Russo, G. and Fernandez-Pello, A.C., "Predictions of the Dependence on the Opposed Flow Characteristics of the Flame Spread Rate Over Thick Solid Fuels," 2nd Int. Symp. of Fire Safety Sci., (accepted) Japan, June 1988.

Amos, B. and Fernandez-Pello, A.C., "Ignition and Flame Development of a Vaporizing Conmbustible Surface in a Stagnation Point Flow," submitted to Combustion Science and Technology (1988).

Di Blasi, C., Cresticelli, S., Russo, G. and Fernandez-Pello, A.C., "Model of the Flow Assisted Spread of Flames Over a Thin Charring Combustible," 22nd Symposium (Int.) in Combustion (accepted), Seattle, WA, August 1988.

Zhou, L., Fernandez-Pello, A.C. and Cheng, R., "Flame Spread in an Opposed Turbulent Flow," submitted for publication in Combustion and Flame (1988).

Fernandez-Pello, A.C., "Controlling Mechanisms of Flame Spread," presentation given at Naples University, Italy, November 1987, and at Sydney University, Australia, June 1988.

APPENDIX A

FLAME SPREAD IN AN OPPOSED TURBULENT FLOW

by

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Presented at the 1988 Fall Technical
Meeting/Western Section of the Combustion
Institute, Laguna Beach, CA, October 17-18, 1988

ABSTRACT

An experimental study is presented of the influence on the spread of flames over the surface of a solid combustible of the turbulence intensity of a gas flow opposing the direction of flame propagation. In the study, the flow velocity and its turbulent intensity are varied to observe the effect of these flow parameters on the rate of flame spread over thick PMMA and thin filter paper sheets. Also observed is their effect on the extinction of the flame. The results show that for thick PMMA sheets the spread rate first increases and then decreases as the turbulent intensity is increased. The presence of a maximum appears to be the result of the flow transition from laminar to turbulent that influences the heat transfer process from flame to fuel. Through interferometric photographs it is shown that the decrease of the spread rate with the turbulence intensity is primarily due to the convective cooling of the region near the flame front. For thin paper sheets the spread rate always decreases as the turbulence increases. The observed differences between the thick PMMA and the thin paper results are probably due to their different mechanism of heat transfer ahead of the flame. It is also found that extinction of the flame occurs at lower flow velocities for higher turbulence intensities. This result, which is unexpected, suggests that convective cooling and/or flame stretch, and no turbulent mixing, are the major effects of the flow turbulence on the extinction of a spreading flame.

INTRODUCTION

In most practical cases the spread of fire occurs under turbulent flow conditions. Flow turbulence can affect both the heat transfer and chemical kinetics mechanisms that control the flame spread process. In opposed flow flame spread, turbulence could produce an increased convective cooling of the unburnt fuel surface and gas region ahead of the flame. Also, it could increase the conductive heating of the solid due to the enhanced heat transfer in the burning region. The former effect should result in a decrease of the flame spread rate as the flow turbulence increases. The latter in an increase. Similarly, turbulence mixing could affect the flame spread process by either favoring the mixing of fuel vapor and oxidant and thus enhancing the combustion reaction, or by diluting the fuel vapor mixture with oxidant which could weaken the reaction. Determination of the role of these different mechanisms is necessary to understand and predict the turbulent spread of fire.

With the exception of the work of Orloff et al, [1] for upward turbulent flame spread over large PMMA sheets, and of Saito and co-workers [2,3] for upward turbulent spread of flames over PMMA and wood sheets, no systematic experiments have been performed to date to determine the effect of turbulence on the flame spread process. This is the objective of this work. The work consists of a parametric study of the spread of flames over thick and thin fuels in a turbulent air flow opposing the direction of propagation. The parameters varied are the flow velocity and its turbulence intensity. The effect of these parameters on the rate of flame spread and on the flame extinction is reported.

Experimental Installation and Procedure

The experimental apparatus consists of a small scale combustion tunnel, designed to conduct combustion experiments under varied flow conditions, and the supporting instrumentation, based primarily on optical and thermocouple measuring methods. A schematic diagram of the installation is shown in Fig. 1. The tunnel has a settling chamber 0.89 m long with a square cross section 0.3 m by 0.18 m, that is connected to the tunnel test section by a converging nozzle with a reduction area of 5.5 to 1 in 0.3 m. The tunnel test section is 0.6 m long and has a rectangular cross section 13 mm wide and 76 mm high. The side walls are made of 6 mm Pyrex glass, and the floor and ceiling sides are made of 25.4 mm thick Marinite sheet. The tunnel is mounted horizontally on a three axis positioning table. The positioning of the table is accomplished with lead screws actuated with computer controlled stepping motors. The system permits positioning the test section with respect to the stationary optical instrumentation at 0.1 mm spacing.

For the thick fuel experiments the specimen is mounted flush in the Marinite floor with its upstream edge placed 15 mm from the exit of the tunnel convergent nozzle. In the present work the fuel specimens are 12.7 mm thick PMMA (Rohm and Mass, Plexiglas G) sheets, 76 mm wide by 0.3 m long. The thin fuel specimens are 0.33 mm thick Whatman filter paper, 76 mm wide by 0.3 m long. The paper sheets are mounted in a metallic frame by inserting them in metallic spikes placed on the sides of the frame [4]. The paper is positioned in the middle of the test section to permit unrestricted burning over both surfaces. The paper sheets are dried in an oven for twenty-four hours prior to their use in the experiments.

The gas flow in the tunnel is supplied either from centralized compressed air or from bottles of compressed oxygen and nitrogen. The individual flow rates are controlled and measured with critical nozzles. Turbulence is generated by means of grids, or perforated plates, placed at the exit of the tunnel converging nozzle. A prescribed turbulence intensity is obtained through a combination of flow velocity and plate blockage ratio. As a consequence high turbulence intensity could not be obtained at very low flow velocities. The distribution of turbulence intensity through the test section is characterized by an initial region, approximately 40 mm where the turbulence decays sharply, followed by a 0.2 m region of practically constant turbulence, and a final region where the turbulence decays again due to entrainment effects at the test section exit. The gas velocity and turbulence intensity are measured with a one component LDV (TSI) operating in the forward scattered mode. The laser source is a Spectra Physics Ar.-Ion laser with a 2 W total output power. The signal is processed with a TSI Doppler processor and transferred to a micro-computer (IBM/AT).

The experimental installation also includes a laser interferometric system that can be operated either as a Mach-Zehnder Interferometer or as a Holographic Interferometer. In this work the former arrangement was used to provide qualitative information about the effect of the flow turbulence on the flame and thermal layer structure. In addition to the interferometer, the installation contains a thermocouple based set-up for gas and solid phase temperature measurements.

The rate of flame spread is measured by timing visually the pass of the flame over previously ruled marks on the fuel surface. For PMMA sheets the flame spread process is initiated by igniting the top downstream edge of the sheet with a propane torch. The filter paper sheets are ignited with an electrically heated nichrome wire placed in close contact with the paper at its downstream edge.

RESULTS

1. Thick PMMA sheets.

The measurements of the flame spread rate over PMMA sheets as a function of the opposed air flow velocity are shown in Fig. 2 for several values of the turbulence intensity. Because of the difficulty of producing high turbulence intensity at low flow velocities, no data was taken at those conditions. The data correspond to averages of three different tests. The spread rate was measured in the test section region that has an approximately constant turbulence intensity.

The results of Fig. 2 for low turbulence intensity show that the spread rate first increases sharply as the flow velocity is increased and then decreases. The initial increase appears to be the result of a transition from a mixed flow type flame spread to a forced flow one. At low flow velocities, normal buoyancy tends to lift the flame from the fuel surface, which results in reduced heat transfer from flame to fuel and consequently in a slower spread rate. The effect of buoyancy on the flame and thermal layer location can be observed by comparing the interferograms shown in Fig. 3 for flow velocities of 0.2 and 0.5 m/sec. It is seen that for 0.5 m/sec the thermal layer is thinner, and the flame slightly closer to the surface, than for 0.2 m/sec, which confirms the above argument. The decrease of the flame spread rate with the opposed flow velocity at higher air velocities is in agreement with the previous results of Fernandez-Pello et al. [5]. As inferred in that work, and later predicted theoretically, [6], the decrease is the result of gas phase chemical kinetics effects. As the opposed flow velocity increases the residence time of the fuel vapor/air mixture ahead of the flame decreases. For constant chemical time this results in a slow down of the combustion reaction at the flame leading edge that sustain the propagation of the flame. This effect is observed to occur at all turbulence intensity levels. At flow velocities larger than 2 m/s the flame spread rate is so slow that the PMMA surface recedes, producing a stagnation region that acts as a flame holder. Thus, for gas velocities larger than 2 m/s the flame propagation is really a mass burning process rather than a flame spread process and is not considered here.

The effect of turbulence intensity on the flame spread rate can also be deduced from the results of Fig. 2. This is presented in Fig. 4 for three value of the flow velocity. It is seen that for all flow velocities the flame spread rate first increases and then decreases as the turbulent intensity increases. The maximum occurs at approximately 6% of the turbulence intensity. This result may reflect the differences in the boundary layer that take place during the transition from laminar to turbulent flow (Fig. 5). For PMMA, heat conduction through the solid is an important flame spread mechanism [7]. Thus, the thinning of the boundary layer that occurs as the flow changes from laminar to turbulent should result in an increase of the flame spread rate because the heat transfer to the solid increases. At low turbulence intensities this effect appears to be more important than the potential enhancement of the fuel convective cooling that should occur as the flow becomes more turbulent. Another possible mechanism that should be considered is an enhancement by the flow turbulence of the fuel vapor and air mixing at the flame leading edge, which could result in a stronger gas phase reaction and consequently in a faster flame spreading velocity. Although we think that the former mechanism is the more likely to occur, there is not enough available information at this point to resolve the issue.

The results of Figs. 2 and 4 also show that once in the turbulent flow regime, the flame spread rate decreases as the turbulent intensity increases.

This effect seems to be the result of convective cooling of the fuel surface and gas at the region in the vicinity of the flame leading edge. The sequence of interferograms of Fig. 5 shows this clearly. It is seen that as the turbulence intensity is increased the thermal layer fluctuates strongly, sometimes becoming very thin near the flame front. This indicates the inducement by the turbulent eddies of cold air from the free stream toward the fuel surface, which results in both a cooling of the fuel surface and of the gas phase chemical reaction. Both are effects that tend to decrease the rate of flame spread.

2. Thin paper sheets

The results of the measurements of the variation with the air flow velocity and turbulence intensity of the flame spread rate over thin paper sheets are presented in Fig. 6. In this case, the flames do not propagate (extinguish) in gas flows with velocities larger than 1.5 m/s. The low flow velocities at which the tests had to be conducted limited the miximum range of turbulence intensities attainable to 15%. From the results of Fig. 6 it is seen that for all turbulence intensities the spread rate decreases as the opposed gas velocity increases. The decrease in the low velocity region, however, is small. This again appears to be the influence of buoyancy on the flame spread process at low flow velocities. This influence is not as noticeable as in the case of PMMA probably because with paper the flames are smaller and consequently less buoyant. The stronger decrease of the flame spread rate with the flow velocity observed for the larger air velocities is in agreement with the results of Fernandez-Pello et al. [5]. As it was discussed in that work, this appears to be the combined effect of convective cooling and weakening of the chemical reaction (smaller residence time) that take place as the opposed flow velocity increases.

The influence of the turbulence intensity on the flame spread rate is also deduced from the results of Fig. 6. It is seen that in this case the spread rate always decreases as the turbulence intensity increases, with no apparent difference during the transition from laminar to turbulent as observed with PMMA. This is possibly the result of the different mechanisms of heat transfer that control the spread of the flame for PMMA or paper. For thin paper sheets, heat transfer through the gas ahead of the flame is the dominant mechanism of heat transfer during the spread of the flame [7]. Thus, the thinning of the boundary layer during the transition from laminar to turbulent flow should have a secondary effect in comparison with the enhancement of the convective cooling caused by the flow turbulence. It is therefore understandable that for flames spreading over paper sheets the simple appearance of flow turbulence could result in a decrease of the spread rate due to both convective cooling of the gas and cooling of the gas phase chemical reaction.

An interesting result obtained in these experiments is the effect of flow turbulence intensity on the extinction of the flame. This is shown in Fig. 7 where the gas velocity at which extinction is observed is presented as a function of the turbulence intensity. It is seen that flame extinction occurs at lower flow velocities when the turbulence intensity is increased. This result, although it is in general agreement with the other flame spread results, is somewhat unexpected since turbulence is often viewed as a means to enhance fuel combustion processes. The fact that in this case the flow turbulence tends to facilitate the flame extinction indicates that convective cooling of the reaction zone, and/or flame stretching effects, are the dominant mechanisms in the flame extinction process, and that the enhancement of the fuel/air mixing by the turbulence has a secondary influence on the gas phase reaction.

CONCLUDING REMARKS

The detailed parametric study conducted in the present work of the spread of flames in an opposed turbulent flow has shown that turbulence intensity has a significant effect on the rate at which the flame spreads, and on the conditions leading to its extinction. The study has introduced a whole new aspect of the flame spread problem that is of special interest given the fact that most practical fires take place under turbulent flow conditions. The nature of the results indicate that the flow turbulence may affect both the heat transfer and the chemical kinetic mechanisms that control the spread of the flame. Although throughout this paper phenomenological arguments are given in an attempt to explain the different experimental observations, the data acquired is not sufficient to prove with certainty that the arguments are correct.

In order to fully understand the effect of turbulence on the flame spread process it appears that it may be necessary to study its influence in each one of the flame spread controlling mechanisms, individually. This could be done by conducting experiments under conditions where the flame spread process is controlled by only heat transfer effects (high oxygen concentration and low gas velocity) or by only gas phase chemical kinetic effects (low oxygen concentration and/or high flow velocity). Also important would be the identification of the non-dimensional parameters that control the turbulent flow flame spread process, and the subsequent correlation of the results in terms of these parameters.

Also interesting is the observation that an increase in the flow turbulence causes an earlier extinction of the spreading flame. The fact that this result is contrary to the more common observation that turbulence favors the combustion reaction by enhanced mixing suggests that the extinction of a spreading flame may be controlled by mechanisms that are somewhat different than those in free flames. The elucidation of this result deserves further attention.

ACKNOWLEDGEMENTS

The authors would like to thank Professor R. Bilger for his useful suggestions concerning the design of the combustion tunnel and the organization of the experiments. This work was supported by the National Bureau of Standards under Grant No. 60NANB7D0737.

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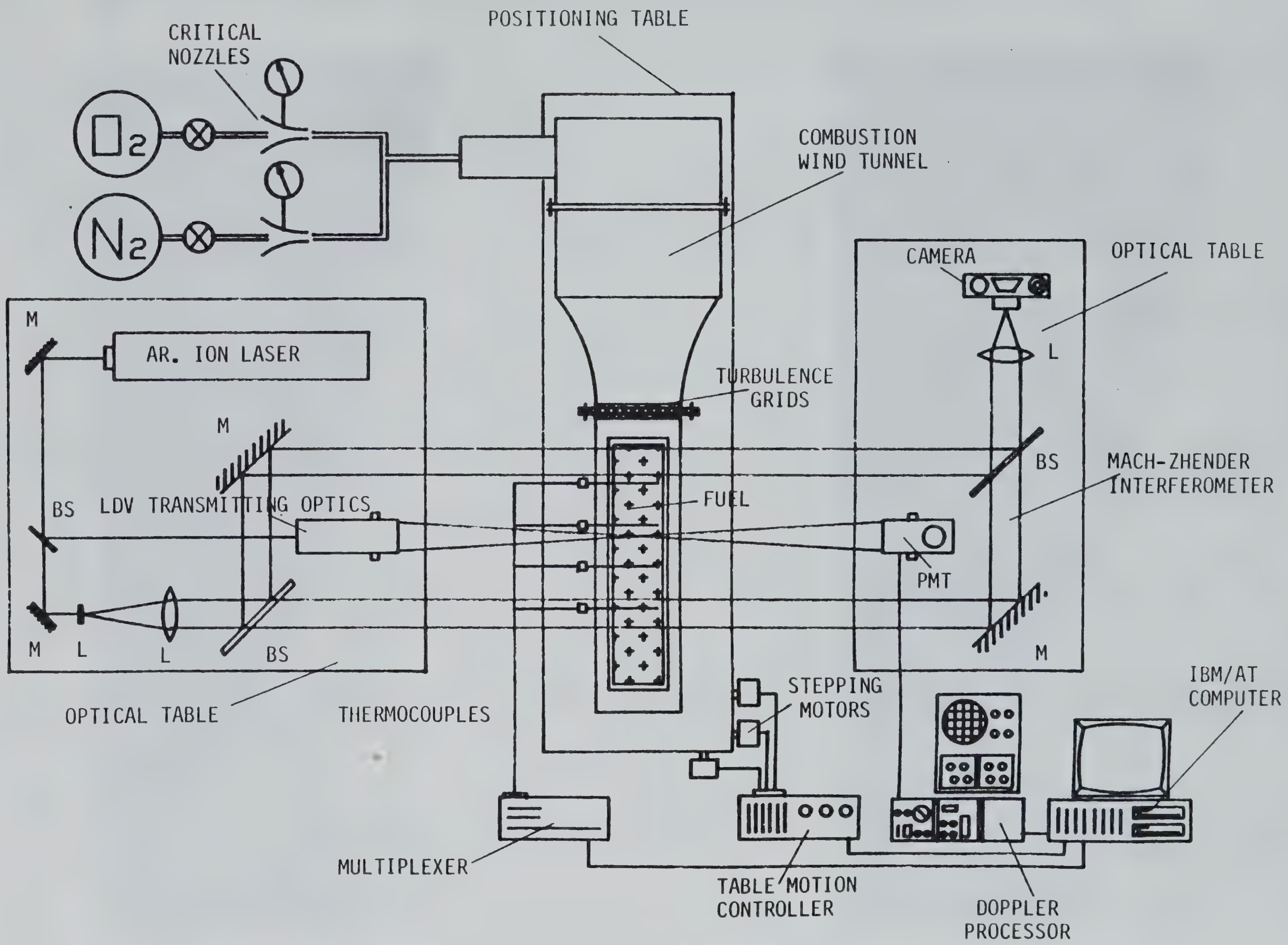

CRITICAL NOZZLES
POSITIONING TABLE
O2
N2
COMBUSTION WIND TUNNEL
CAMERA
OPTICAL TABLE
M
AR. ION LASER
L
TURBULENCE GRIDS
M
BS
MACH-ZHENDER INTERFEROMETER
BS
LDV TRANSMITTING OPTICS
FUEL
PMT
M
L
L
BS
M
OPTICAL TABLE
THERMOCOUPLES
STEPPING MOTORS
IBM/AT COMPUTER
MULTIPLEXER
TABLE MOTION CONTROLLER
DOPPLER PROCESSOR

Fig. 1

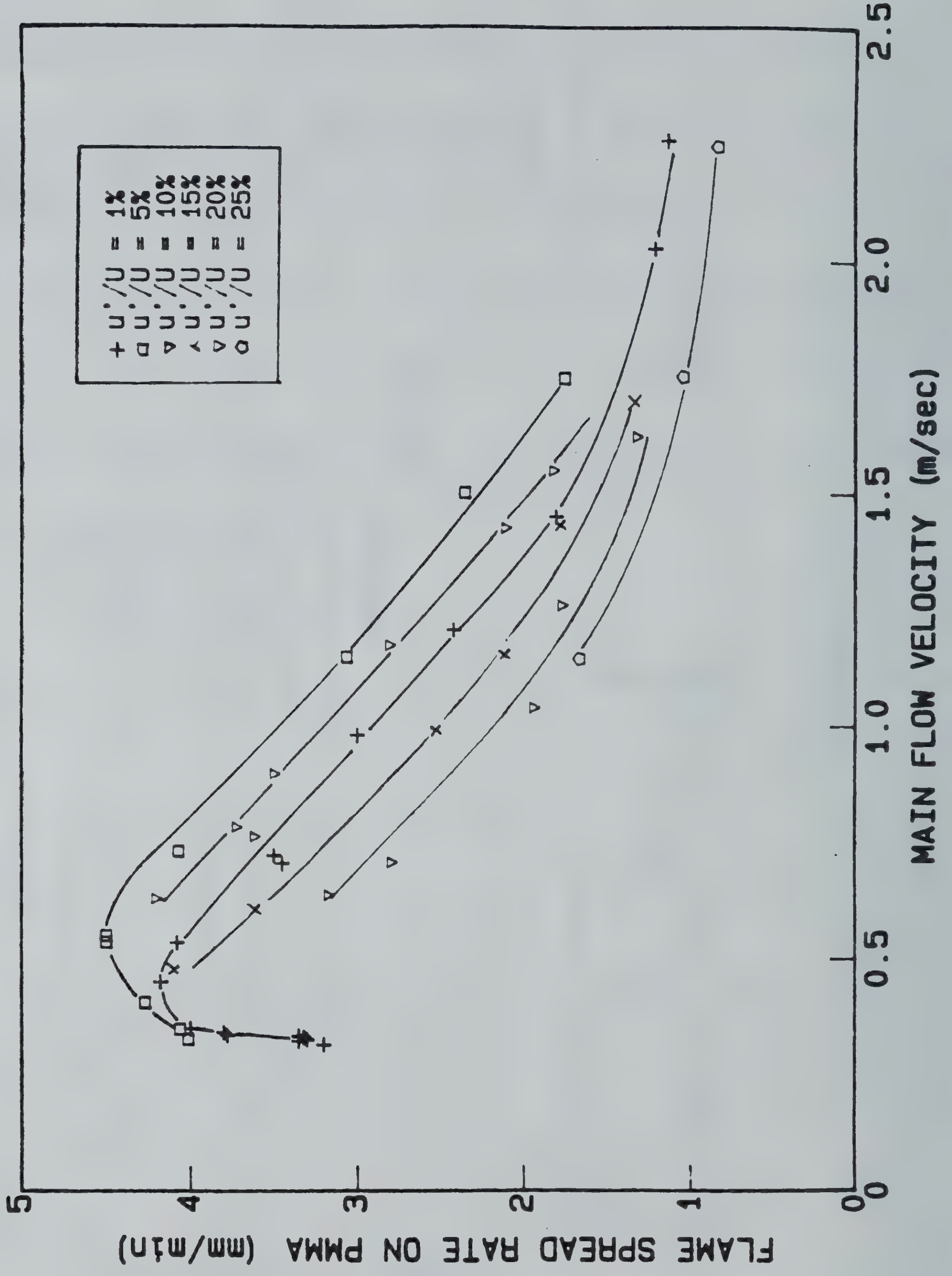
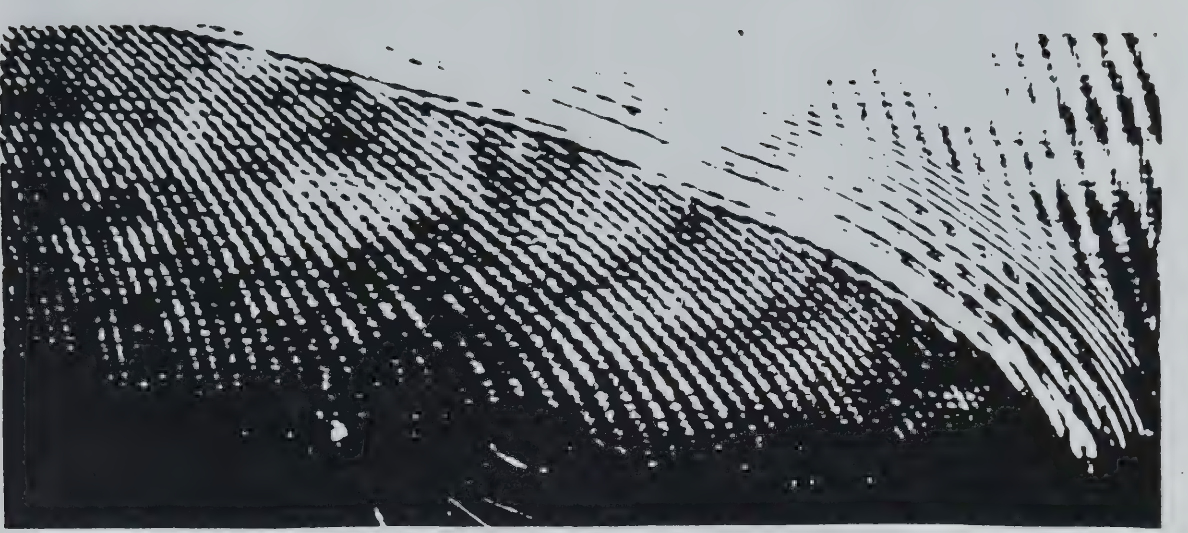
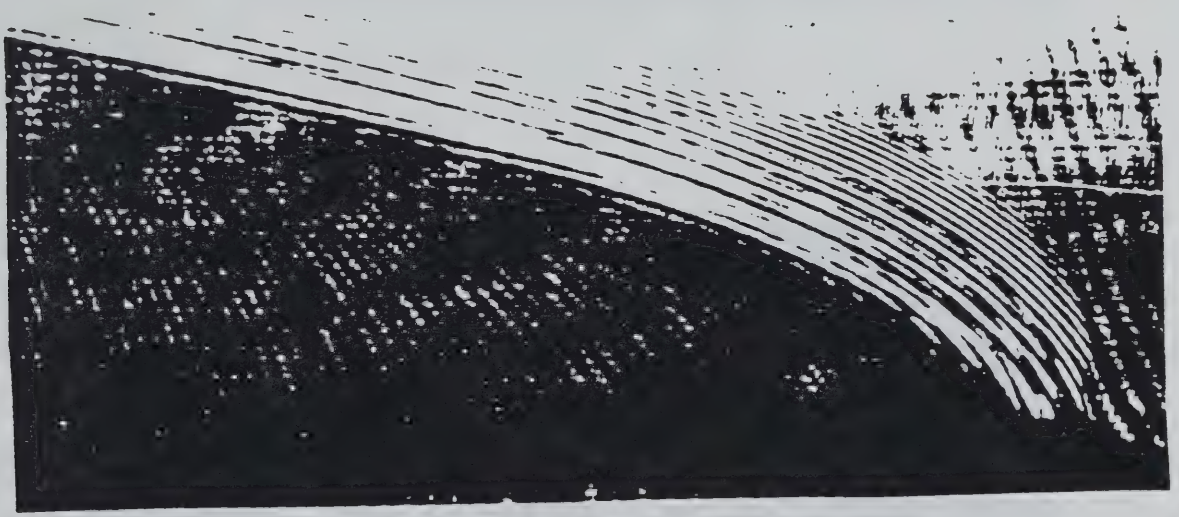

FLAME SPREAD RATE ON PMMA (mm/min)
MAIN FLOW VELOCITY (m/sec)
0
1
2
3
4
5
0
0.5
1.0
1.5
2.0
2.5
+ u'/U = 1%
□ u'/U = 5%
△ u'/U = 10%
x u'/U = 15%
▽ u'/U = 20%
○ u'/U = 25%

FIGURE 2.



3.a. $U_m = 0.2$ m/s $U'/U = 1\%$



3.b. $U_m = 0.5$ m/s $U'/U = 1\%$

FIGURE 3.

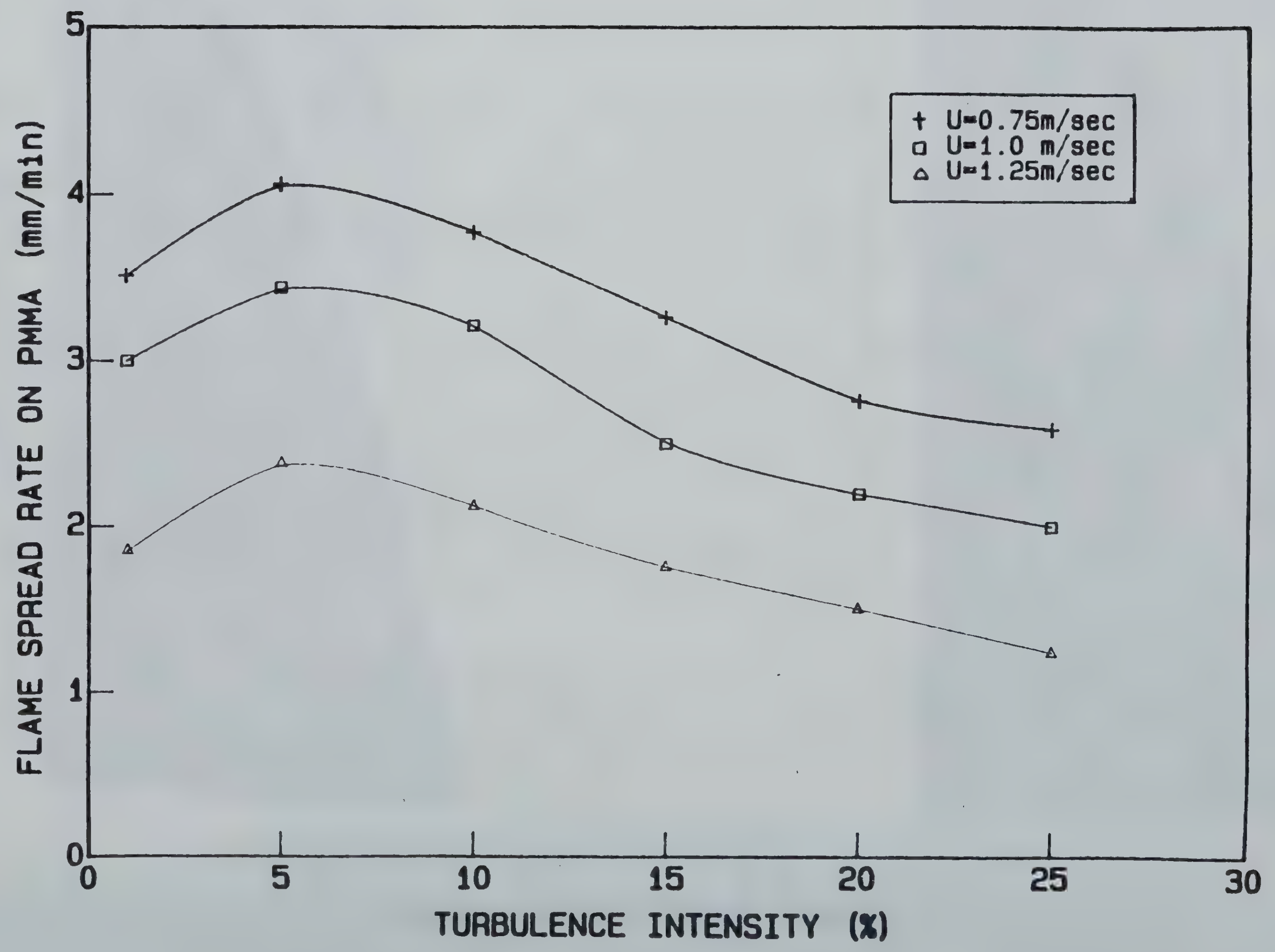
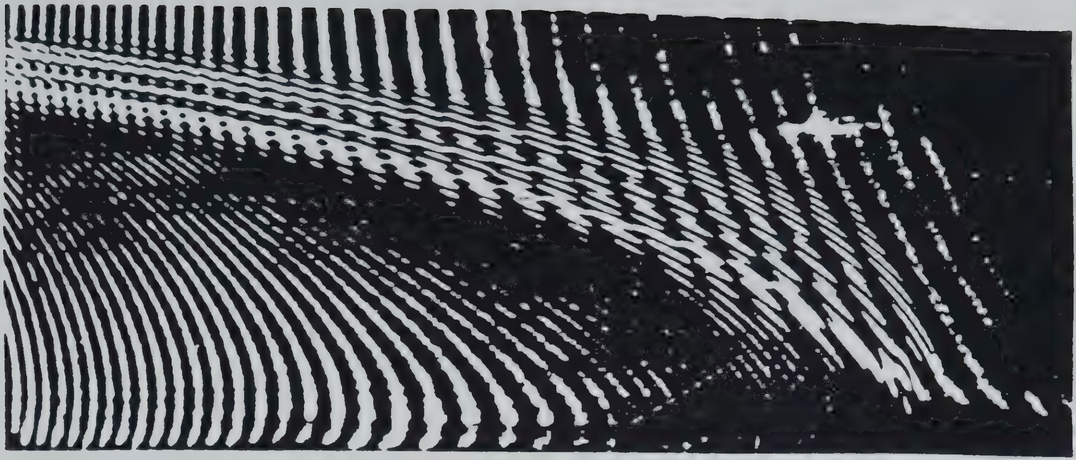
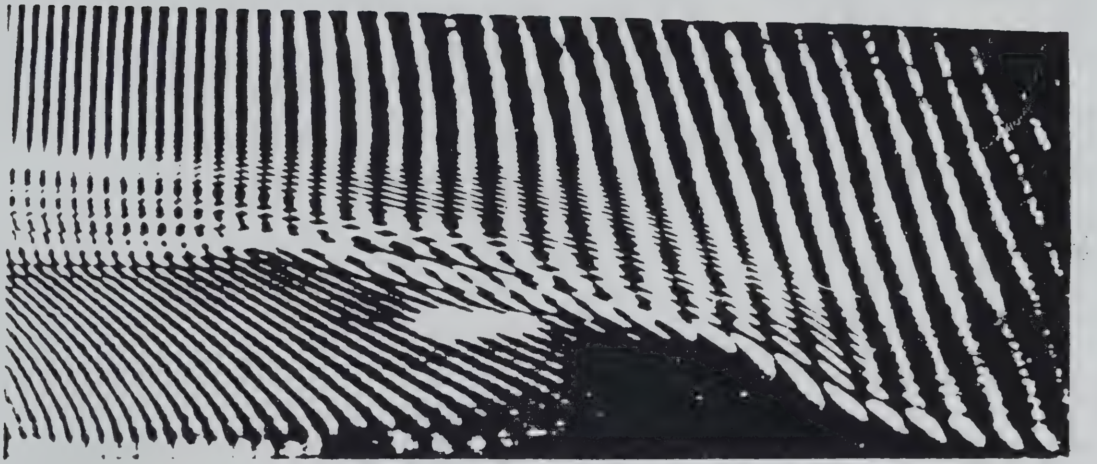

+ U=0.75m/sec
□ U=1.0 m/sec
△ U=1.25m/sec
FLAME SPREAD RATE ON PMMA (mm/min)
0
1
2
3
4
5
0
5
10
15
20
25
30
TURBULENCE INTENSITY (%)

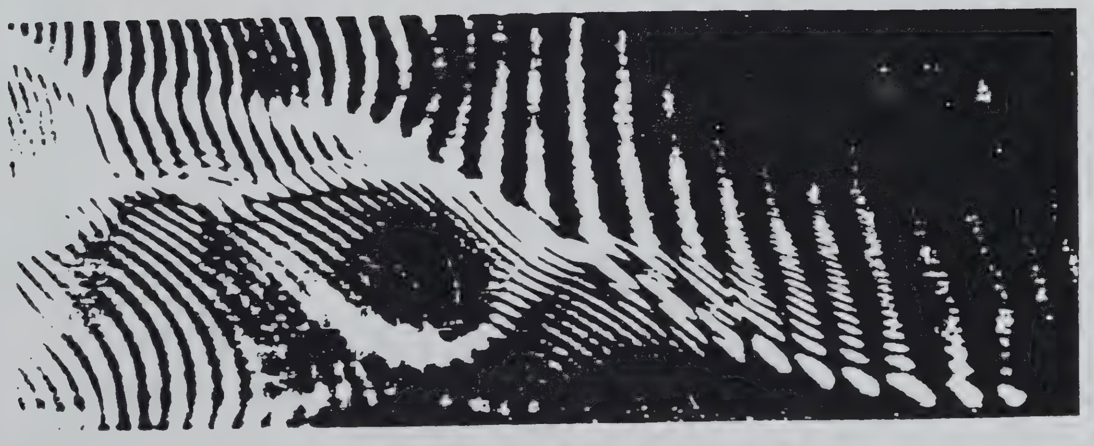
FIGURE 4.



5. a. $U_m = 1$ m/s $U'/U = 1\%$

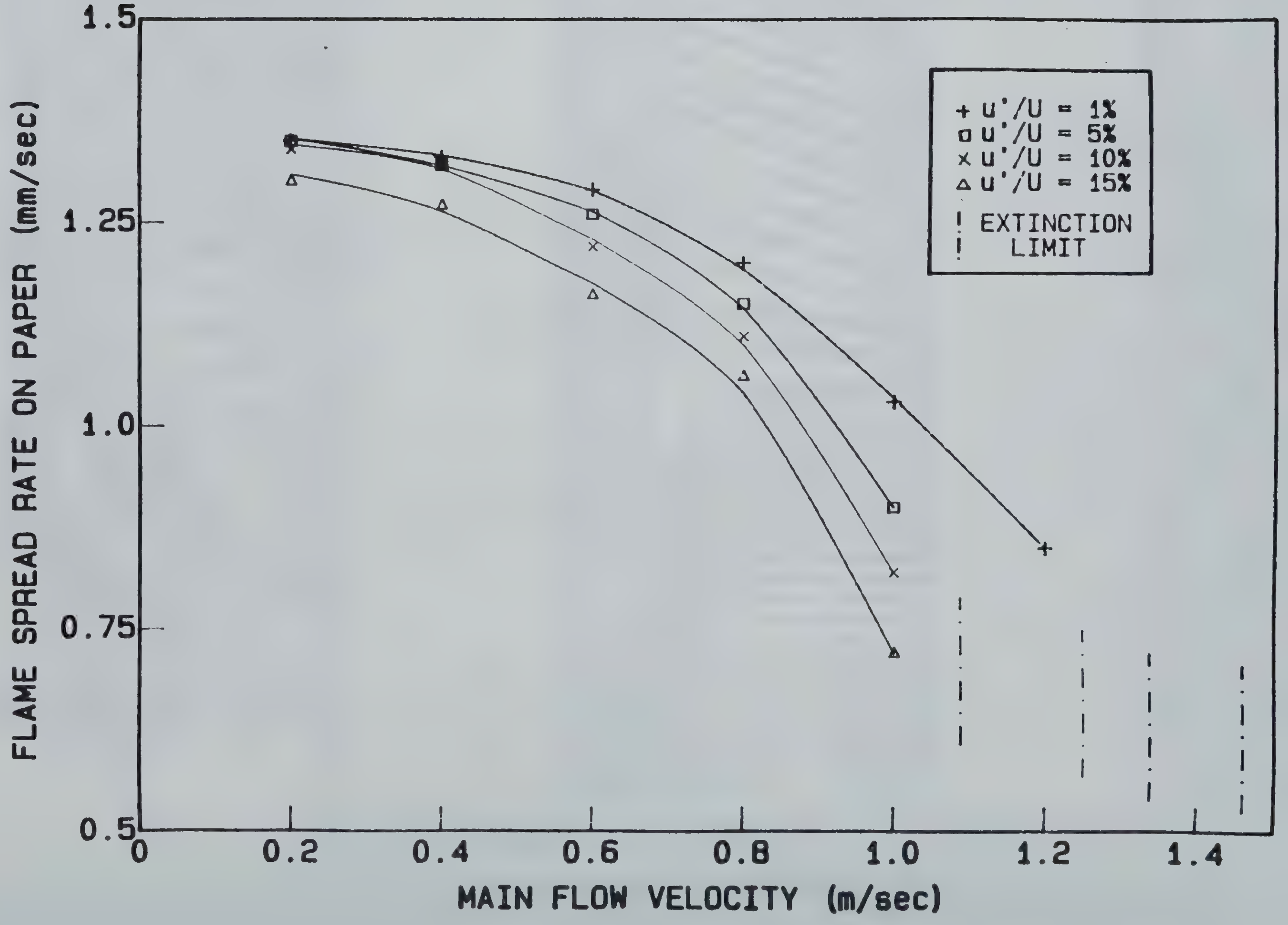


5.b. $U_m = 1$ m/s $U'/U = 10\%$



5.c. $U_m = 1$ m/s $U'/U = 25\%$

FIGURE 5.



+ u'/U = 1%
□ u'/U = 5%
× u'/U = 10%
△ u'/U = 15%
EXTINCTION LIMIT
1.5
1.25
1.0
0.75
0.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
FLAME SPREAD RATE ON PAPER (mm/sec)
MAIN FLOW VELOCITY (m/sec)

FIGURE 6.

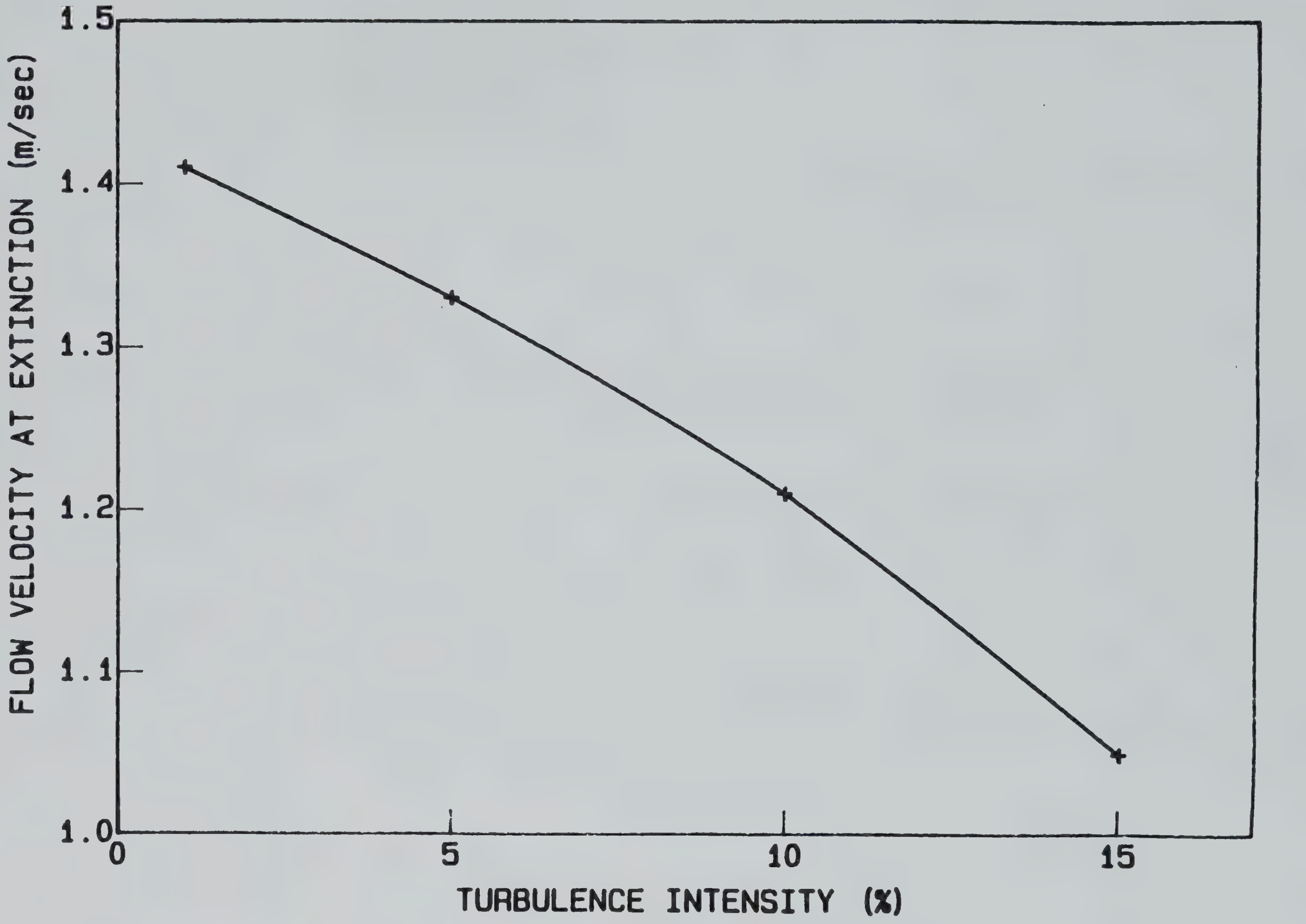

1.5
1.4
1.3
1.2
1.1
1.0
0
5
10
15
FLOW VELOCITY AT EXTINCTION (m/sec)
TURBULENCE INTENSITY (%)

FIGURE 7.

APPENDIX B

MODEL OF THE FLOW ASSISTED SPREAD OF FLAMES OVER A THIN CHARRING COMBUSTIBLE

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Key words:

(10) Fire
(19) Modeling and Simulation
(23) Propagation Rates

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ABSTRACT

A theoretical model is developed of the spread of a flame over the surface of a thin combustible solid in a gas flow moving in the direction of flame propagation. Many of the simplifying assumptions made in previous studies have been removed. The combustion reaction and the solid pyrolysis are modeled respectively with a one-step, second order, and with a zero order Arrhenius rate. The charring of the solid is modeled by treating the solid as a two component material, the combustible component that gasifies, and the char that remains occupying the initial solid volume. To simplify the mathematical solution of the problem a Hagen-Poiseuille flow is prescribed, thus eliminating the need for using the momentum conservation equations. The transient, reactive, gas phase balance equations of energy and species coupled at the interface to the solid phase balance equations are solved numerically to describe the evolution of the flame and solid properties, and through them to predict the variation with time of the flame, pyrolysis and burn-out distances and their dependence on the flow velocity. The application of the analysis to the spread of flames over paper sheets in a concurrent air flow gives good agreement with previous experimental data. Particularly important is the description of the transition of the flame spread process from an initial accelerative stage to a final steady state. The transition is determined by the interaction between the progress of the pyrolysis and the burn-out fronts, and their effects on the flame length. According to boundary layer analyses, the model predicts a spread rate that increases, although weakly, with the flow velocity, while the experiments show a spread rate that first increases at low flow velocities and then becomes constant as the flow velocity is increased. Possible reasons for this disagreement are discussed in the work. Finally the predicted flame extinction limit due to increased concurrent velocity is very close to the experimentally determined value.

INTRODUCTION

The concurrent, or flow assisted, mode of flame spread is of particular importance in the development of a fire because of its rapid and consequently hazardous character. If the combustible is thin, the propagation of the "pyrolysis" or "burning" fronts is further characterized by the consumption of the combustible in the burning region upstream. This produces a propagating "burn-out" front. The interaction between the two fronts affects the characteristics of the flame downstream and consequently the flame spread rate.

Very few analyses have been published of the concurrent spread of flames over a thin combustible. The works of Refs. [1-3] all provide approximate analytical solutions of the problem by using simplifying assumptions. A detailed discussion of these assumptions is given in the review of Ref. [4]. The analyses provide explicit expressions for the rates of spread of the pyrolysis and burn-out fronts in the form of power law dependences on time that partially describe the initially acceleratory part of the spread process experimentally observed[1,5]. However, they cannot predict the transition to the final steady state of the process observed in the experiments, the phenomena related to the extinction of the flame or the effect of char formation. The studies of Ref. [6-8] do include char formation in the modeling of flame spread process, but their application to the present problem is limited because they are basically thick solid analyses that include many restrictive assumptions.

The present work provides a more accurate description of the problem by removing some of the critical assumptions made in the previous analyses of the problem. Finite Arrhenius type rates are introduced to describe the gas phase reaction and the pyrolysis of the combustible, thus removing the flame sheet and ignition temperature approximations. Solid properties that vary from their original material to their char value are included to describe more accurately the combustible "burn-out" process.

MODEL

The model describes the spread of a flame over the surface of a thin combustible solid in an oxidizer flow moving in the direction of flame propagation. A schematic of the model is shown in Fig. 1. A fuel sheet of specified length and thickness is placed in a wall of a channel where the gas flow is prescribed to be a constant properties Hagen-Poiseuille flow. The initiation of the flame spread process is achieved by igniting a small portion of the fuel sheet at its upstream edge by means of a pilot flame, which is active for a short period of time (.25 s). During this period the gas velocity is set equal to zero. Once ignition occurs, the pilot flame is turned off and the flow velocity set to its specified value, initiating the flame spread process. The magnitude of the pilot flame and ignition time are kept to a minimum to reduce the effects of the ignition process on the flame spread rate. As the combustible component of the solid gasifies the remaining char occupies the same volume of the initial solid.

In the formulation of the mathematical model, several additional assumptions are made to simplify the solution. In the gas the combustion reaction is modeled with a one-step irreversible chemical reaction of the form $\nu_F + \nu_O \rightarrow \nu_P$, with a second order Arrhenius rate. With the flow field prescribed and constant thermal properties, the gas phase governing equations are:

- energy balance

$$c_p\rho_g[\partial T_g/\partial t + u\partial T_g/\partial x] = w\Delta H + k_g[\partial T^2_g/\partial x^2 + \partial T^2_g/\partial y^2] \qquad (1)$$

-mass blance for chemical species

$$\rho_g[\partial Y_i/\partial t + u\partial Y_i/\partial x] = w\mu_i + D\rho_g[\partial Y^2_i/\partial x^2 + \partial Y^2_i/\partial y^2] \quad (2)$$

$$\sum_i Y_i = 1 \qquad i = I,\ P,\ O,\ F \quad (3)$$

where $w = -A_g\exp(-E_g/RT_g)\ Y_F Y_O \rho_g{}^2$ and $\mu_i = M_i\nu_i/M_F\nu_F$

In the solid phase analysis the solid is assumed to be thermally thin, and therefore the temperature and density distributions across its thickness are uniform. The pyrolysis of the combustible is modeled following the approach proposed by Kung [9] for wood pyrolysis. The solid density and specific heat change during the pyrolysis process from their initial values to their final values for the char. The pyrolysis reaction is assumed to be described by an expression of the for $S \rightarrow \nu_G + \nu_C$, which implies a rate of material disappearance and product appearance given by:

$$-d\rho_s/dt = M_S/M_G/\nu_G\ d\rho_G/dt = M_S/M_C/\nu_C\ d\rho_C/dt$$

During pyrolysis the actual density of the material can be written in the form:

$$\rho_s(t) = \rho_a(t)\ \ (1 - \rho_{cf}/\rho_{s0}) + \rho_{cf} \quad (4)$$

The pyrolysis rate is assumed to be described by a zero order Arrhenius expression of the form:

$$d\rho_s/dt = -A_s\rho_a\ \exp(-E_s/RT_s) \quad (5)$$

Combination of Eqs. (4) and (5) gives finally:

$$d\rho_s/dt = -A_s/[1 - (\rho_{cf}/\rho_{s0})]\ (\rho_s - \rho_{cf})\ \exp(-E_s/RT_s) \quad (6)$$

With solid properties uniform across its thickness, the solid phase energy balance equation becomes:

$$\rho_s c_s \partial T_s/\partial t = -d\rho_s/dt\ \{L + [-\rho_{s0}/(\rho_{s0} - \rho_{cf})c_a +$$
$$\rho_{cf}/(\rho_s - \rho_{cf})c_c - c_p]\ (T_s - T_o)\} + k_g\partial T_g/\partial y/\tau +$$
$$(\partial/\partial x)\ [\partial(k_s T_s)/\partial x] \quad (7)$$

In Eq. (7) the radiant flux from the flame to the surface and from the surface to ambient have been neglected for simplicity reasons. It is acknowledged, however, that the error introduced by this simplification could be significant for relatively large scales and sooty flames. It is worth noting that although the conductive term in the solid phase balance equation has been retained, it has been found that this term does not play an important role in the propagation process and it can be dropped from the equation without change in the results. This is to be expected since, for thermally thin solid fuels, the heat transfer to the unburnt material occurs mainly through the gas phase[4,11].

The initial conditions for the above equations are that the combustible sheet and gas flow are at ambient conditions, i.e., at $t = 0$ the gas temperature and species mass fractions are: $T_g = T_0$, $Y_F = Y_P = 0$, $Y_0 = Y_{00}$ and $Y_I = Y_{I0}$ and the solid temperature and density are $T_s = T_{s0}$ and $\rho_s = \rho_{s0}$. The boundary conditions are: $T_g = T_0$, $Y_0 = Y_{00}$, $Y_F = Y_P = 0$, $Y_I = Y_{I0}$ at the inflow; at the outflow: $\partial T_g/\partial x = 0$, $\partial Y_i/\partial x = 0$ for $i = I, P, 0, F$; the upper wall of the channel is inert and non-conducting: $\partial T_g/\partial y = 0$, $\partial Y_i/\partial y = 0$ for $i = I, P, 0, F$. At the gas solid interface the boundary conditions that apply until burn-out are: $\rho_g D\, \partial Y_F/\partial y = m\,(Y_F - 1)$; $\rho_g D\, \partial Y_i/\partial y = m\,(Y_i)$ for $i = I, 0, P$, $T_g = T_s$, with the pyrolysis mass flux given by $m = A_s \rho_s \exp(-E_s/R\, T_s)$. In the fuel burned region a zero normal gradient condition is applied to the temperature and species concentrations, i.e., split boundary conditions are applied at the burn-out front.

The system of non-linear, coupled differential equations (1-2) and (6-7) with their initial and boundary conditions are solved numerically. The finite difference method of Ref. [12] is used for the gas phase equations and a splitting method, that combines a fourth order Runge-Kutta method and the backward scheme, is used to solve the solid phase equations. A variable integration grid is used in the x and y directions.

RESULTS

The above model is applied to describe the spread of a flame over the surface of a thin paper sheet in a concurrent flow of air. The paper sheet is .37 m long and $.33\text{x}10^{-3}$m thick. These dimensions were selected the same as those used in the experiments of Ref. [5] to compare the theoretical and the experimental results. The properties used for the paper are[13]:
$c_s = c_a = c_c = 1.255$ [kJ/kg K], $K_s = 1.325\text{x}10$ [kJ/s m k], L = - 753 [kJ/kg], $\rho_{s0} = 0.6\text{x}10^{-3}$ [kg/m^3], $\rho_{cf} = 0.03\text{x}10^{-3}$ [kg/m^3]. The data used for the pyrolysis reaction are $A_s = 1\text{x}10^{10}$ [s^{-1}], $E_s = 125{,}520$ (kJ/Kmole] which are in the range of values suggested in Ref. [14]. The gas properties are taken as those for air at ambient temperature. The one-step reaction model for the gas phase combustion refers to the monomer cellulose, and the kinetic and thermokinetic constants are: $A_g = 1\text{x}10^{11}$ [sm^3/kg], $E_g = 112968$ [kJ/kmole] (Ref. [13]) and $\Delta H = 11857$ [kJ/kg]. The value for the heat of combustion is taken equal to that reported in Ref. [15], and it gives good agreement for the predicted and experimental[16] values of the gas phase temperature. The grid size in the x direction is very fine close to the ignition zone ($\Delta x = 0.12\text{x}10^{-2}$m for a length of 0.02 m), then it varies linearly from $0.12\text{x}10^{-2}$m to $0.94\text{x}10^{-2}$m for a length of 0.05 m, and it becomes constant ($\Delta x = 0.84\text{x}10^{-2}$m) in the remaining part of the integration domain. For the y direction, a step equal to $0.5\text{x}10^{-4}$m is used for a length of $0.12\text{x}10^{-2}$m close to the fuel surface, a linear variation to $0.55\text{x}10^{-3}$ for $y = 0.5\text{x}10^{-2}$m and a constant distribution for the remaining part of the integration domain. The time integration step is equal to $5\text{x}10^{-4}$s. It

has been found that a further decrease in the integration steps does not change the accuracy level of the results.

A characteristic example of the predicted flame structure and solid properties distributions is shown in Fig. 1. The calculations are for a flame spreading over a paper sheet in a concurrent flow with a mean velocity of 0.67 m/s at a time of 2 s, after the initiation of the flame spread process. In order to give a good representation of the flame structure details only a small part of the integration domain is plotted. The gas phase isotherms (Fig. 1a) and species equi-concentrations (Fig. 1b) distributions show that the flame, except at its upstream leading edge and tip, has a diffusional character with a relatively large reaction rate. Also, except at the flame leading edge, the normal temperature and species concentrations gradients are very large and the streamwise ones small. At the flame leading edge and tip regions, a quenching layer is formed near the fuel surface and there is penetration of fuel and oxidizer through the reaction zone. This indicates that in these regions the reaction rate is slow and that finite rate kinetics must be employed to describe them accurately. The solid temperature (Fig.1a) and density (Fig. 1b) distributions show the relationship between the gas and the solid phase processes. A significant increase in the solid temperature does not occur until the arrival of the flame tip. From then on the temperature increases steadily until the solid starts to pyrolyze at which point the temperature levels off marking the pyrolysis front. The initiation of fuel pyrolysis is best observed from the density profiles of Fig. 1b. The pyrolysis initiation is characterized by a decrease in the solid density, which continues until all the fuel is pyrolyzed and only the constant density char is left. The termination of the pyrolysis process is also characterized by a sharp increase in the solid temperature due the accumulation of heat by the char. Either the constant char density or sharp temperature increase determines the location of the burn-out front.

The evolution of the temperature field, as the flame spreads, is presented in Fig. 2 for three consecutive times and the same flow conditions as above. The strong increase of flame length with time is the result of the large amount of excess fuel vapor that is produced as the pyrolysis region, and the pyrolyzed fuel, increase. The fuel vapor is convected downstream from the pyrolysis front reacting with the air and consequently extending the flame in the downstream region. The results of Fig. 2 also show the propagation of the upstream leading edge of the flame. This propagation is linked to that of the burn-out front, and consequently to the solid phase processes. Under extinction conditions, however, the position of the leading edge would be controlled by gas phase kinetic mechanisms. Under these conditions the burn-out front propagation rate could be faster than that of the pyrolysis front which could result in the extinction of the flame.

The predicted evolution of the solid temperature and density profiles during the spread of the flame for the above stated conditions is shown in Fig. 3. These profiles provide information about the initiation of the solid heating process and pyrolysis, and of the depletion of the combustible component. This information is used to determine the location and progress of the pyrolysis and burn-out fronts and from them to calculate their rates of spread. The location of the pyrolysis front is determined from the temperature profiles by defining a reference or "pyrolysis front temperature", a method that is commonly used in the experiments[3,5]. In this work this reference temperature is taken as 618 K as in the experiments of Ref. [5]. The location of the burn-out front is easier to determine because when all the combustible component of the solid is gasified, its density becomes that of the char and the temperature increases sharply as there is no fuel gasification.

Results as those presented in Fig. 3 are used to produce the predictions of Fig. 4 for the variation with time of the pyrolysis and burn-out distances under several flow conditions. The experimental data reported in Ref. [5] are also included in the figure for comparison purposes. To reduce the effect of the fuel ignition process, the distances and time are given with reference to the respective values once ignition has been achieved. It is seen that the model predicts well the experimental data with a spread process that is initially accelerative and that tends towards a steady state as the flame spreads over the solid surface. This is the result of the variation with time of the length of the pyrolysis region that initially increases very fast as the pyrolysis front propagates and the burn-out front still remains stationary. Once the burn-out front starts to propagate, the rate of increase of the pyrolysis length decreases as the burn-out front accelerates. When later the rates of spread of both fronts become of the same value, the pyrolysis length and consequently the rate of flame spread tends to a constant value. In the same figure, the flame distances have been plotted. The flame tip is defined as the location of the downstream edge of the local fuel to oxygen equivalence ratio iso-line of value 1. The predicted values for the flame length are also very close to the experimental ones. Better quantitative agreement between theory and experiments could be obtained for a given flow velocity by varying some of the parameters controlling the pyrolysis process such as the pre-exponential factor and activation energy of the pyrolysis reaction, heat of evaporation, char density, etc.

It is felt, however, that the required computer time is not justifiable given the overall approximations of the model and some of the uncertainties in the measurements[5].

A difference between the model and the experimental results is the predicted and measured dependence of the flame spread rate on the flow velocity. From the results of Fig. 4 it is seen that the model predicts a spread rate that increases, although weakly, with the flow velocity, while the experiments show a spread rate that first increases at low flow velocities and then becomes constant as the flow velocity is increased[5].

The predicted dependence on the flow velocity of the steady state spread rate of the pyrolysis front, deduced from the distances reported in Fig. 4 by differentiation with respect to time, is presented in Fig. 5. Also the experimental results of Ref. [5] have been included for comparison purposes. It is seen that the model predict a weak increase of the pyrolysis front spread rate with the flow velocity. A similar dependence can be deduced from Fig. 4 for the flame and burn-out fronts. Although these dependences can be explained with phenomenological descriptions[5] of the flame spread process, they disagree with the experimental observations of Ref. [5]. There are several reasons thay may explain these discrepancies. One is the type of flow prescribed in the present model which cannot predict the growth of the velocity boundary layer and consequently cannot predict accurately the surface heat flux distributions. However, the models using the boundary layer approximation for the flow field also predict similar dependences, which seems to indicate that this is not the primary problem. Another reason is the model simplified description of the filter paper pyrolysis and degradation process, which could result in inaccurate predictions of the burn-out spread rate. The description of the gas phase reaction is another potential source of error, although a sensitivity analysis of the gas phase reaction Arrhenius parameters effects on the spread rate did not show major differences in the results. Finally a fact that should be kept into account is that the conclusions described in Ref. [5] may not be totally accurate because of the experimental difficulties encountered and the small range of flow velocities tested[5].

As in the experiments, the extinction limit (fig. 5) is characterized by a discontinuous drop in the flame spread rate from a finite value to zero. In the simulations it has been observed that a gas velocity of 2.18 m/s is the maximum value for which the spread of flames in air can occur. For higher velocities there is no propagation after ignition. The predicted limit, which is very close to that observed in the experiments (2 m/s), depends on the parameter values used to describe the combustion in the gas phase and the solid fuel pyrolysis.

CONCLUDING REMARKS

The present model provides a detailed description of the flame structure, as it spreads, and predictions of the flame, pyrolysis and burn-out distances variations that are in good agreement with the experimental observations. Also the determined extinction limit is very close to that experimentally observed. Particularly important is the description of the interaction between the progress of the pyrolysis and burn-out fronts that results in the transition of the flame spread process from an initial accelerative stage to a final steady state. Another important contribution is the consideration of longitudinal diffusion during the initial stage of the flame spread and in the description of the burn-out process since the boundary layer approximation cannot be applied at the upstream leading edge of the flame. The dependence of the spread rate on the flow velocity is still a subject not fully resolved. Although the experiments indicate that it becomes constant for relatively large flow velocities, the present and previous models of the problem predict a spread rate that increases weakly with the flow velocity. The dependence on the flow velocity is physically understandable since the spread of the pyrolysis front is controlled by mechanisms that are somewhat different than those of the burn-out front (mass burning rate), and it is the interaction between the spread of the two fronts that finally determines the flame spread rate. In addition there are uncertainties in the experimental data that suggest that perhaps the experimental conclusions are inaccurate and not the prediction of the model. This issue can only be resolved with more experimental information or more accurate models of the flame spread process.

The results of this analysis also indicate that simplified versions of the present model could predict, it not in detail, certain aspects of the flame spread process. An example of such simplified models is the analysis of Saito et al[7] for the upward turbulent spread of flames over charring materials. These simplified models would be particularly useful as input in models of fire development in rooms, or in the application of tests to measure the flammability of materials.

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NOMENCLATURE

A	preexponential factor
c_p	gas phase specific heat at constant pressure
c	solid phase specific heat
D	gas phase diffusion coefficient
E	activation energy
ΔH	heat of combustion per unit mass fuel
k	thermal conductivity
l	length
L	heat of pyrolysis
m	pyrolysis mass flux
M	molecular weight
Q	surface heat flux
R	universal gas constant
T	temperature
t	time
u	gas velocity
u_m	mean gas velocity
V	spread rate
w	reaction rate
x	coordinate parallel to the fuel surface
y	coordinate normal to the fuel surface
Y	mass fraction species i
ν	stoichiometric coefficient
ρ	density
τ	solid half thickness

SUBSCRIPTS

a	combustible component in the solid
b	burn-out
c	char
cf	final char
C	solid fuel that remains as char
f	flame
F	fuel
g	gas phase
G	solid fuel that vaporizes
I	inert
i	species
O	oxidant
p	pyrolysis
P	product
s	solid phase
0	ambient conditions

LIST OF FIGURES

Fig. 1 - Schematic of model. Predicted flame structure and solid properties distributions for a mean flow velocity equal to 0.67 m/s, at t = 2 s after ignition: a) gas isotherm field and solid temperature distribution; b) species equi-concentrations fields and solid density distribution. The external isotherm, for the gas phase, is 600 K and the increment is 300 K. The isolines for the fuel mass fraction correspond to 0.4, 0.3, 0.2, 0.1, 0.001; for the oxygen mass fraction the internal line is 0.05 and the increment is 0.05.

Fig. 2 - Predicted evolution of the temperature field for a mean flow velocity of 0.67 m/s, a) t = 1 s, b) t = 1.75 s, c) t = 2.25 s. The external isotherm, for the gas phase, is 600 K and the increment is 300 K.

Fig. 3 - Predicted evolution of the solid temperature and density during the spread of the flame in a flow with a mean velocity of 0.67 m/s from t = 4 s to t = 15 s and with an increment of 1 s.

Fig. 4 - Predicted variation with time of the flame, pyrolysis and burn-out distances for several flow conditions. The experimental data of Ref. [5] are included for comparison.

Experiments of Ref. [5]:

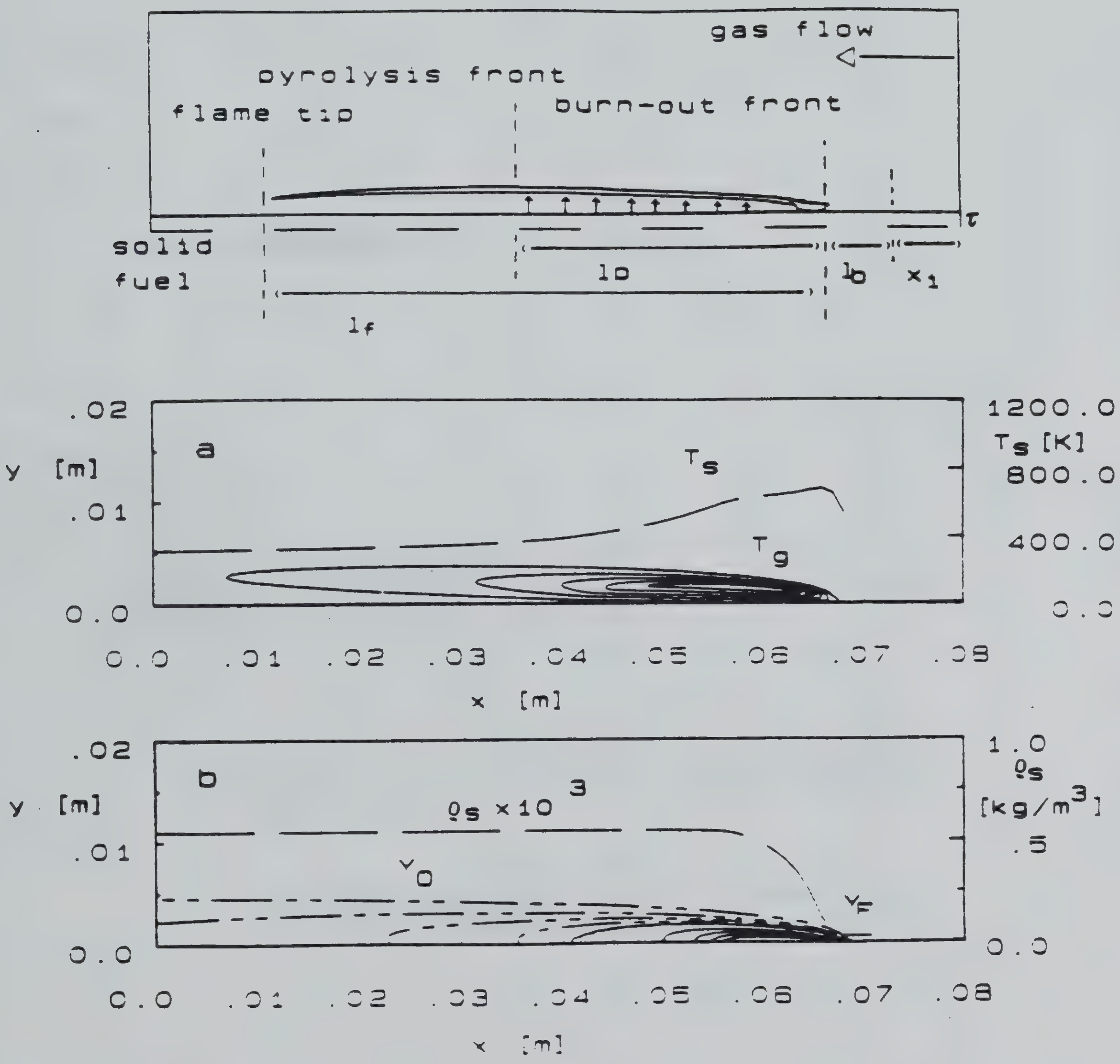
gas velocity	flame	pyrolysis	burn-out
0.625 m/s	+	◇	◆
1.00 m/s	x	△	▲
2.00 m/s	*	□	■

Model: ______._ flame, ______ pyrolysis, ______--- burn-out;

mean gas velocity: a) 0.67 m/s, b) 1 m/s, c) 1.33 m/s, d) 2 m/s.

Fig. 5 - Predicted dependence on the flow velocity of the pyrolysis spread rate. The experimental data of Ref. [5] are included for comparison.

Fig. 1


gas flow
pyrolysis front
flame tip
burn-out front
solid
fuel
τ
l_p
l_b
x_1
l_f
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y [m]
.02
.01
0.0
T_s
T_g
1200.0
T_s [K]
800.0
400.0
0.0
0.0 .01 .02 .03 .04 .05 .06 .07 .08
x [m]
b
y [m]
.02
.01
0.0
$\varrho_s \times 10^3$
Y_O
Y_F
1.0
ϱ_s
[kg/m^3]
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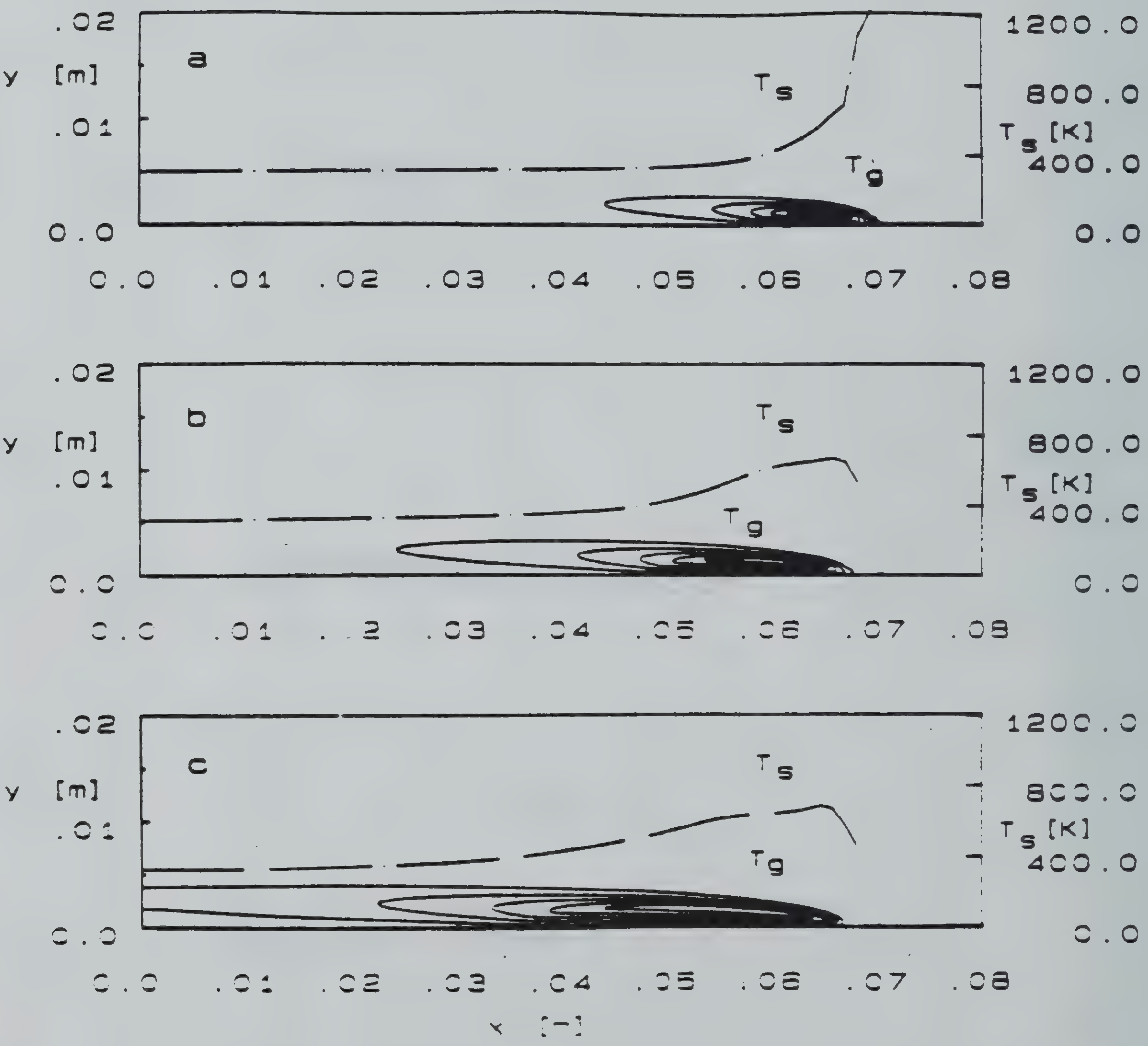
0.0
0.0 .01 .02 .03 .04 .05 .06 .07 .08
x [m]

Fig. 2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b
c
y [m]
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.01
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T_s
T_g
T_s [K]
1200.0
800.0
400.0
0.0
0.0
.01
.02
.03
.04
.05
.06
.07
.08
x [m]

Fig. 3

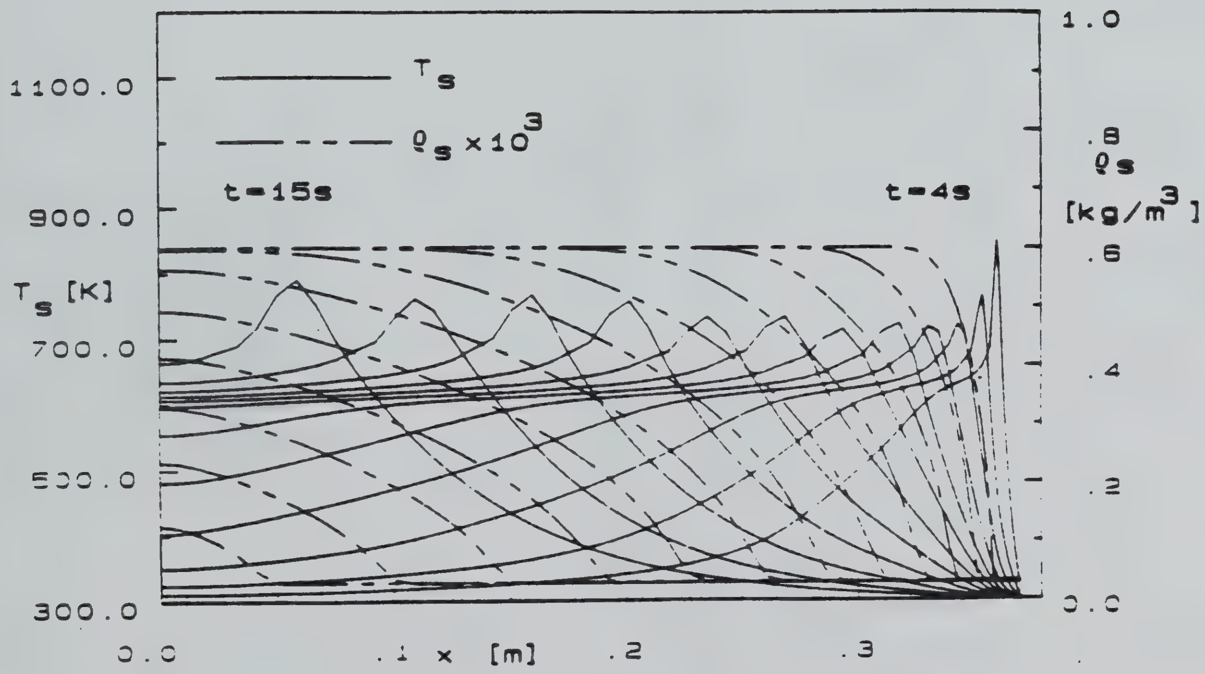

T_s
$\varrho_s \times 10^3$
t=15s
t=4s
1100.0
900.0
700.0
500.0
300.0
T_s [K]
1.0
.8
.6
.4
.2
0.0
ϱ_s [kg/m^3]
0.0
.1
x [m]
.2
.3

Fig. 4

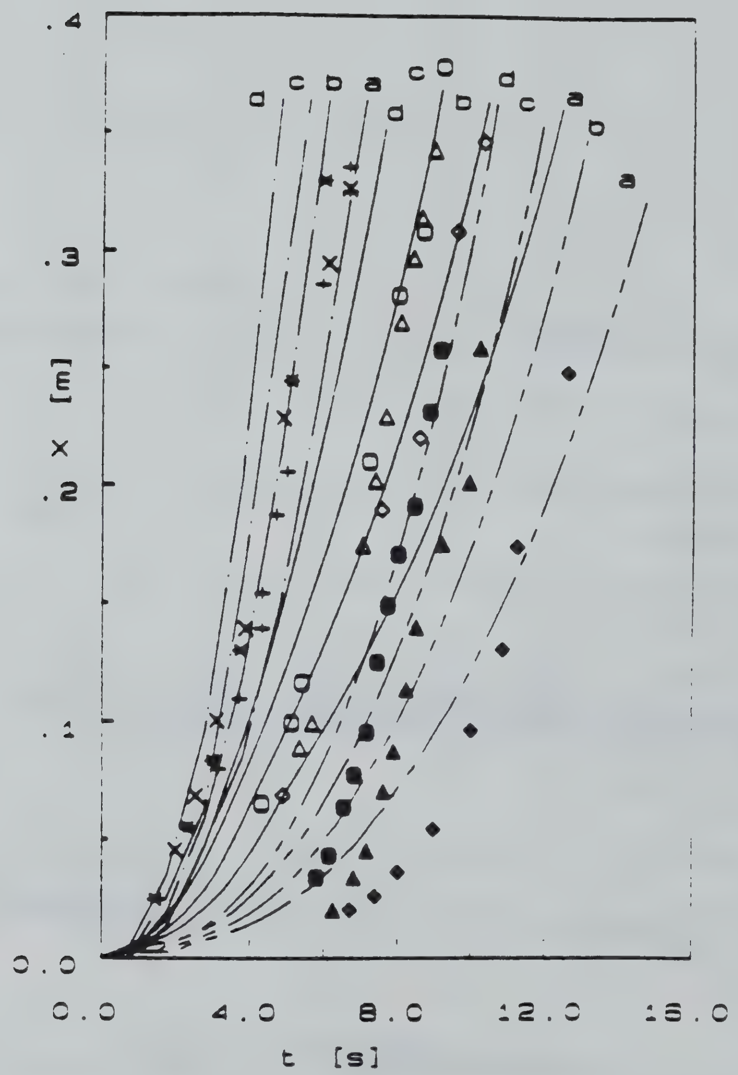
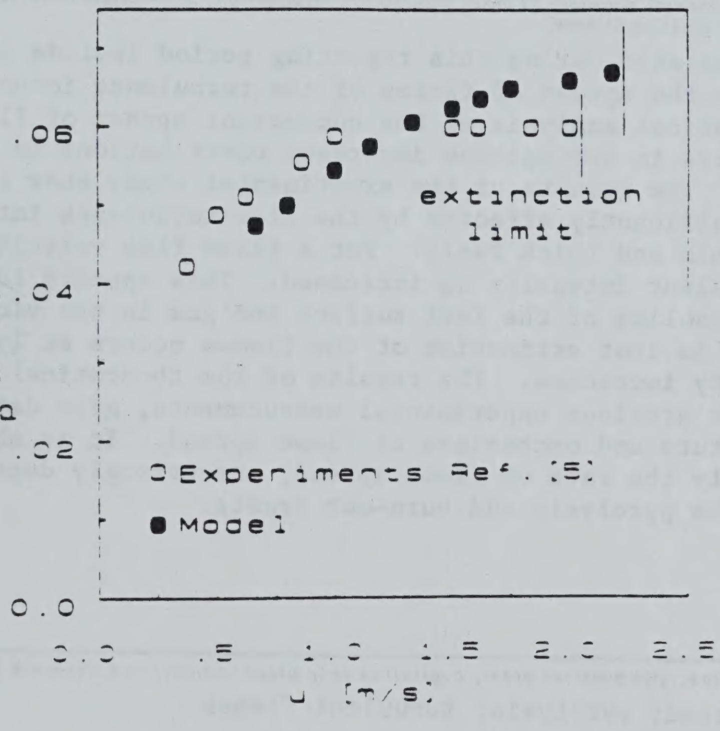


Fig. 5


.06
.04
.02
0.0
Vp [m/s]
extinction limit
Experiments Ref. [5]
Model
0.0
.5
1.0
1.5
2.0
2.5
u [m/s]

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The research tasks completed during this reporting period include an experimental study of the effect on the spread of flames of the turbulence intensity of an opposed air flow, and a theoretical analysis of the concurrent spread of flames over thin fuels. Both studies are in our opinion important contributions in the study of the flame spread process. The results of the experimental study show that the flame spread process is significantly affected by the flow turbulence intensity for flames spreading over both thin and thick fuels. For a fixed flow velocity, the spread rate decreases as the turbulent intensity is increased. This appears to be due to the turbulent convective cooling of the fuel surface and gas in the vicinity of the flame front. Also observed is that extinction of the flames occurs at lower velocities as the turbulent intensity increases. The results of the theoretical analysis, which are in good agreement with previous experimental measurements, give detailed information about the flame structure and mechanisms of flame spread. It is shown that the flame length and consequently the rate of flame spread, are strongly dependent on the interaction between the pyrolysis and burn-out fronts.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

flame length; flame spread; pyrolysis; turbulent flames

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